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Vincent Roche[a,b,c,*], Valentin Laurent[a,b,c], Giovanni Luca Cardello[a,b,c], Laurent Jolivet[a,b,c], Stéphane Scaillet[a,b,c]

[a] Université d'Orléans, ISTO, UMR 7327, 45071 Orléans, France
[b] CNRS/INSU, ISTO, UMR 7327, 45071 Orléans, France
[c] BRGM, ISTO, UMR 7327, BP 36009, 45060 Orléans, France

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ABSTRACT

Since 35 Ma, the kinematics of the Aegean domain has been mainly controlled by the southward retreat of the African slab, inducing back-arc extension. The main structures and associated kinematics are well constrained, but the kinematics of deformation before 35 Ma, coeval with the exhumation of blueschists and eclogites of the Cycladic Blueschist Unit, is still poorly understood. The earlier Eocene syn-orogenic evolution is strongly debated and very different geometrical interpretations and kinematic histories have been proposed in the literature. This study focuses on the high-pressure and low-temperature (HP-LT) parageneses spectacularly exposed and well preserved on Sifnos Island. The new field work provides new structural constraints on the tectonic history of HP-LT units generated in the subduction zone during the Eocene. It further shows how lithological heterogeneities localize strain within an accretionary wedge and how the localisation of strain evolves through time during exhumation. We show, through new geological and metamorphic maps, cross-sections and analyses of kinematic indicators, that Sifnos is characterized by shallow-dipping shear zones reactivating weak zones due to competence contrasts or earlier tectonic contacts. Structures and kinematics associated with these shear zones, show a top-to-the-N to −NE ductile deformation. The lower part of the tectonic pile shows a downward gradient of shearing deformation and is actually a thick top-to-the-NE shear zone, which we name the Apollonia Shear Zone. Through time shearing deformation tends to localize downward, leaving the upper part of the subduction complex preserved from late deformation. The present-day shape and topography of the island is largely controlled by late brittle faults reworking the earlier ductile shear zones. Comparing with the nearby island of Syros, we propose a new tectono-metamorphic evolution of the Cycladic Blueschist Unit, which partly explains the different degrees of retrogression observed on the Cycladic Islands.

1. Introduction

The exposure of high-pressure and low-temperature (HP-LT) metamorphic rocks results from the exhumation of material buried along the plate interface in subduction zones. Part of the exhumation can be achieved during subduction in different ways: 1) by decoupling of crustal units of variable thickness from the subducting lithosphere within the plate interface (Chemenda et al., 1995; Jolivet et al., 2005; Brun and Faccenna, 2008; Agard et al., 2009; Jolivet and Brun, 2010; Ring et al., 2010; Tirel et al., 2013); 2) by circulation of weak material within a thick accretionary complex (corner flow model); 3) in the subduction channel (England and Holland, 1979; Shreve and Cloos, 1986; Platt, 1993; Burov et al., 2001 Gerya et al., 2002). The main difference between the different types of models is the degree of strain localization. The subduction channel concept is highly variable in the literature, from the initial simple double circulation model in the space left between the two plates (England and Holland, 1979; Shreve and Cloos, 1986) to more sophisticated models with several levels of circulation like in Burov et al. (2001). This type of models does not show the details of how tectonic units are finally decoupled from the subducting plate and it only suggests exhumation from large depth in low viscosity material, which implies distributed deformation in the channel. Other models, based on decoupling of crustal units of variable thickness from the subducting lithosphere (Chemenda et al.,

* Corresponding author at: Université d'Orléans, ISTO, UMR 7327, 45071 Orléans, France.
E-mail address: v.roche@brgm.fr (V. Roche).

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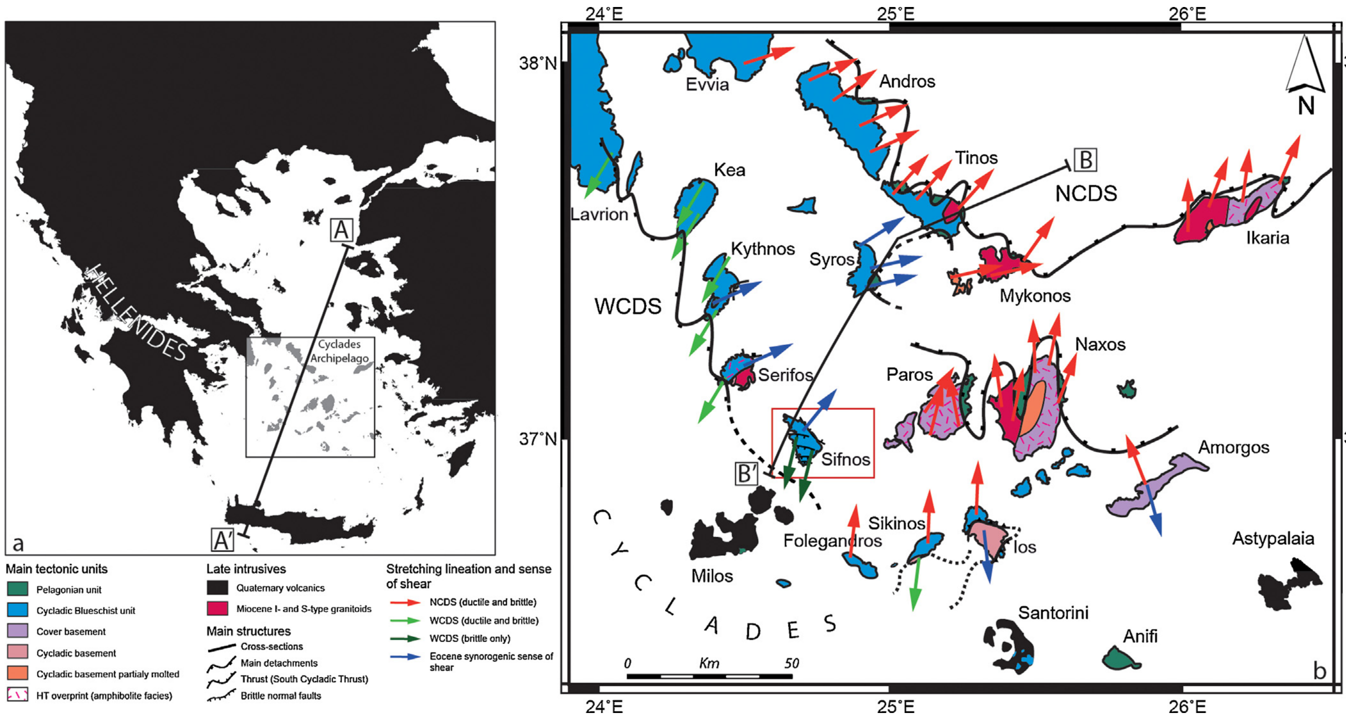

Fig. 1. Tectonic map of the Aegean domain.
Tectonic map of the Aegean domain and schematic geological map of the Cyclades showing the main structures related to both syn-orogenic and post-orogenic episodes, modified after Jolivet and Brun (2010). The original map has been modified incorporating recent works (Kumerics et al., 2005; Rosenbaum et al., 2007; Huet et al., 2009; Grasemann et al., 2012; Augier et al., 2015; Laurent et al., 2015; Beaudoin et al., 2015). Stretching-parallel cross-section through Aegean domain (Fig. 1a) and central Aegean (Fig. 1b) are indicated. Red box: Location of Sifnos.(For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

1995; Jolivet et al., 2005; Brun and Faccenna, 2008; Agard et al., 2009; Jolivet and Brun, 2010; Ring et al., 2010; Tirel et al., 2013), also permit the exhumation of high-pressure rocks. However, the piece of crust is extruded upward between a frontal thrust and a normal fault above, which implies a strong localization close to this interface only. These models only differ from the precedent by the degree of localization of deformation. Depending on the size of the exhumed unit, the model is more or less similar to the basic subduction channel model. The extreme localization can be found in the propositions of Chemenda et al. (1995), or Brun and Faccenna (2008) where the exhumed unit is only one, totally rigid, between the frontal thrust and the normal fault. When exhumed units are more numerous and smaller the general picture is quite similar to the subduction channel model. Some of the main problems are thus the degree and the controlling factors of strain localization in subduction complexes. In this paper we show how strain was localized during exhumation through a new field study.

In the Cycladic Archipelago, the exhumation of HP-LT metamorphic rocks was achieved in two stages: the first stage corresponds to the exhumation within the subduction channel during Eocene and the second stage to the exhumation below shallow-dipping detachments in the back-arc region in the Oligocene and Miocene. In the following, we name the first stage 'syn-orogenic exhumation' as opposed to the second stage 'post-orogenic exhumation' for distinguishing exhumation acquired during lithospheric shortening from exhumation acquired during later lithospheric extension (Jolivet et al., 2003; Jolivet and Patriat, 1999; Jolivet et al., 2003,2013; Bonev and Beccaletto, 2007; Forster and Lister, 2009). The syn-orogenic part of exhumation, which is of concern here, is also controlled by kinematic boundary conditions of the subduction channel, with slab retreat probably favouring fast exhumation (Jolivet et al., 1994; Beaumont et al., 1996; Brun and Faccenna, 2008; Tirel et al., 2013). Metamorphic units may thus have different P-T-time histories, starting within the subduction channel in HP-LT conditions and ending within the back-arc region in high-temperature metamorphic core complexes.

Syros and Sifnos islands are located in the central part of the Cyclades Archipelago (Fig. 1a) and show spectacular preservation of blueschists and eclogites parageneses (Fig. 1b; Altherr et al., 1979; Blake et al., 1981; Avigad et al., 1992; Trotet et al., 2001a,b; Rosenbaum et al., 2002; Philippon et al., 2011) that are worldwide known for the study of the geodynamic processes operating at the plate interface. Several petrological studies, P-T estimates and geochronological constraints are available on these two islands (Altherr et al., 1979; Wijbrans et al., 1990; Avigad, 1993; Lister and Raouzaios, 1996; Trotet et al., 2001a; Schmädicke and Will, 2003; Schumacher et al., 2008; Groppo et al., 2009; Dragovic et al., 2012; Bröcker et al., 2013). However, structural studies devoted to the relations between deformation and metamorphism (Trotet et al., 2001b; Rosenbaum et al., 2002; Ring et al., 2003; Keiter et al., 2004, 2011; Bond et al., 2007; Philippon et al., 2011; Ring et al., 2011), are still debated and different geometrical interpretations and kinematic histories have been proposed rendering difficult the choice of a model for the exhumation mechanism.

In this work, we thus revisit the geology of Sifnos, based on new geological maps at the 1:20,000 scale. Our aim is to study the distribution of deformation through evolving P-T conditions to better describe the distribution of strain within the subduction complex and constrain the mechanisms of exhumation of HP-LT units from the subduction zone.

2. Geological setting

The Aegean domain, located in the eastern Mediterranean Sea (Fig. 1a), has undergone a tectonic and metamorphic evolution defined by two main steps. Firstly, from the late Cretaceous to the Eocene, the Africa-Eurasia convergence has led to the formation of the Hellenides-Taurides chain (see location on Fig. 1a)

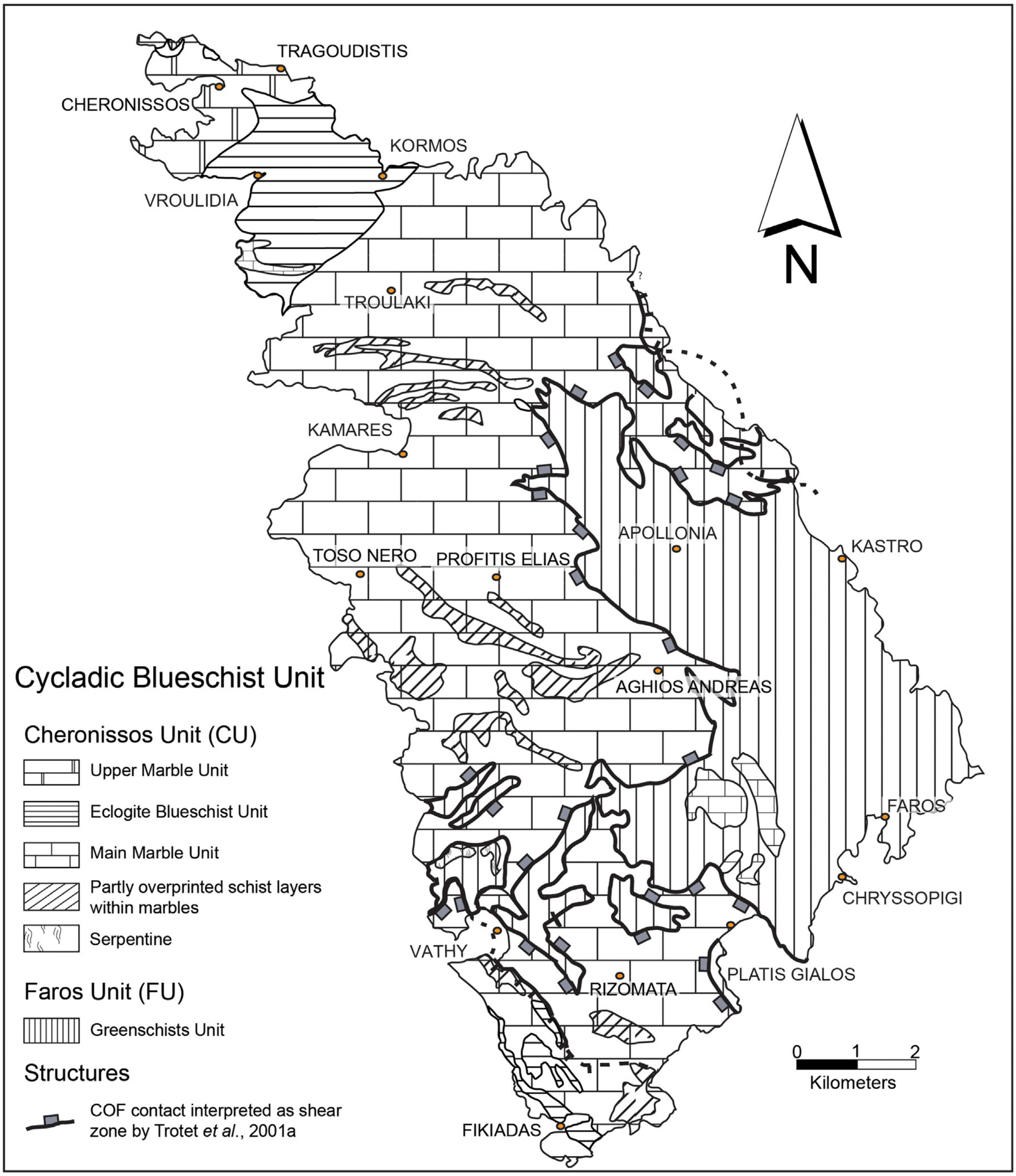

Fig. 2. Simplified geological map of Sifnos modified after Avigad (1993) and Trotet et al. (2001a,b).

that is composed of a stack of oceanic and continental nappes belonging to Apulia (Aubouin, 1957; Jacobshagen et al., 1978; Jacobshagen, 1986; Stampfli, 2000). The stratigraphic sequences of the main Hellenic nappes and their paleogeographic origin can still be recognized and correlations can be made from the mainland to the islands, despite the intensity of later post-orogenic extension (Bonneau, 1984; Jolivet et al., 2004; Van Hinsbergen et al., 2005). Secondly, since 35 Ma, the kinematics in the upper plates of the Mediterranean subduction zones has mainly been controlled by the southward retreat of the African slab (Malinverno and Ryan, 1986; Jolivet and Faccenna, 2000; Jolivet et al., 2008; Jolivet and Brun, 2010), responsible for back-arc extension. The Cyclades archipelago results from the collapse of the Hellenides-Taurides belt caused by this retreating subduction which changed the kinematic boundary conditions from compressional to extensional in the back-arc region (Fig. 1b; Lister et al., 1984; Jolivet et al., 2013).

Extension was recorded in the Rhodope Massif earlier than in the Aegean Sea. The Rhodope Massif is located in the northern part of the studied domain, south of the Balkans. The Rhodope Massif underwent a H*P* metamorphism (i.e. 12–17 kbar, 750–811 °C) with locally ultra-H*P* conditions, no later than the late Cretaceous (Liati et al., 2002; Bonev et al., 2006; Bauer et al., 2007). Then, M*T*-M*P* metamorphism (i.e. 8–10 kbar, 560–650 °C) was recorded in the Paleocene and exhumation of these rocks started in the central Rhodope massif ~55 Ma ago below top-to-the NE ductile-brittle detachments in back-arc domain (Burg et al., 1996; Bonev et al., 2006). Extension started in the Rhodope earlier than in the Cyclades, sometimes in the Eocene (Brun and Sokoutis, 2007). During the same period, syn-orogenic exhumation occurred in the

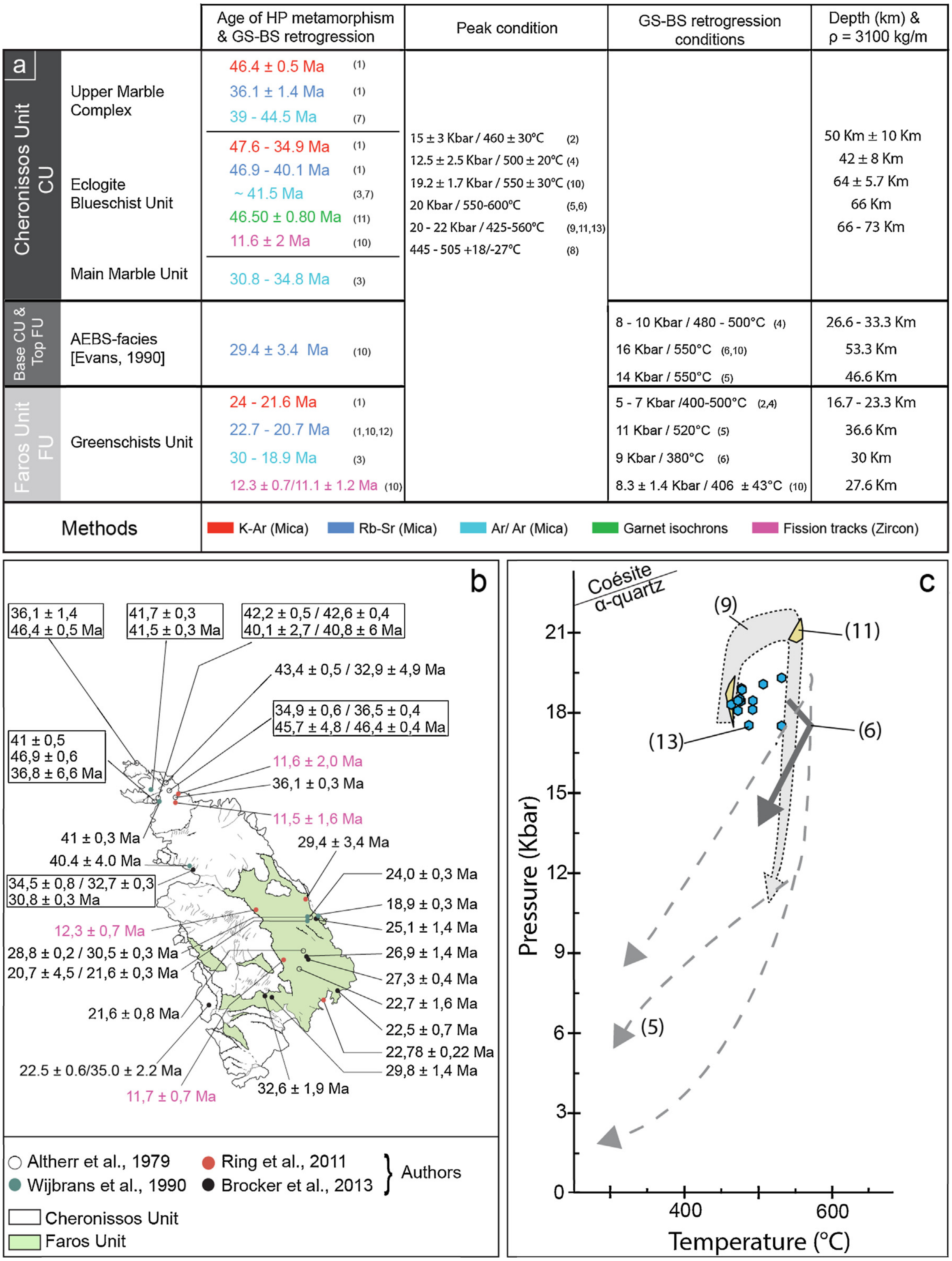

Fig. 3. P–T conditions and deformation ages within Cheronissos and Faros units.
(a) Geological pile on Sifnos showing different ages of metamorphic peak conditions, and blueschist-facies (BS) to greenschist-facies transition (GS) with the associated depths. Superscript numbers indicate the citations, 1) Altherr et al., 1979; 2) Schliestedt and Matthews, 1987; 3) Wijbrans et al., 1990; 4) Avigad et al., 1992; 5) Trotet et al., 2001a; 6) Schmadicke and Will, 2003; 7) Forster and Lister, 2005; 8) Spear et al., 2006; 9) Groppo et al., 2009; 10) Ring et al., 2011; 11) Dragovic et al., 2012; 12) Bröcker et al., 2013; 13) Ashley et al., 2014. (b) Compilation of results of K-Ar, $^{40}Ar/^{39}Ar$ and Rb-Sr ages on phengite, paragonite and fission track on zircon. (c) Detailed P-T path modified after Ashley et al. (2014), subscript numbers indicate the References.(For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Cyclades region within the Hellenic subduction zone and the CBU underwent HP metamorphism at 70–90 km depth whereas partial exposure at the surface of the central Rhodope core complex occurred in the back-arc domain (Jolivet and Brun, 2010). Extension then migrated to the Cyclades some 35 Myrs ago and the Aegean Sea started to form. This new episode of extension associated with a fast migration of the magmatic arc, during slab retreat, while during the first extensional episode, the arc was more steady, suggesting that slab retreat was quite slow (Jolivet and Brun, 2010; see also Menant et al., 2016).

2.1. Cycladic archipelago

The geology of the Cycladic archipelago is divided into three units, which are from top to bottom: the Upper Unit (UU), the Cycladic Blueschist Unit (CBU), and the Cycladic Basement Unit. In this framework, we focus on the CBU that mainly crops out in the central part of Aegean domain (Fig. 1b). This unit is correlated with the Pindos Unit in continental Greece (Bonneau, 1982, 1984) and consists of alternating marbles, metapelites, metabasites and meta-ophiolite. CBU rocks have undergone a dominant HP-LT metamorphism in the Eocene (K-Ar, ^{40}Ar-^{39}Ar and Rb-Sr on phengite after Altherr et al., 1979; Bröcker and Franz, 1998; Huet, 2010), and are particularly well exposed in the mapped area. Different parageneses display contrasting P-T-time evolutions but with the same peak P-T conditions in the eclogite-facies around 21kbar and 550 °C (Trotet et al., 2001b; Groppo et al., 2009; Dragovic et al., 2012; Ashley et al., 2014). This HP-LT metamorphism is partially overprinted by Oligo-Miocene HT-LP metamorphism (Altherr et al., 1979, 1982; Keay et al., 2001; Vanderhaeghe, 2004; Duchene et al., 2006; Bröcker et al., 2013), which took place contemporaneously with back-arc extension. The overprint is generally characterized by greenschist-facies parageneses and locally by amphibolite-facies ones, reaching partial melting conditions in Naxos, Ikaria and Mykonos (Keay et al., 2001; Denèle et al., 2011; Laurent et al., 2015; Beaudoin et al., 2015). The CBU recorded their retrograde peak temperature in the centre of the back-arc area during the Miocene, at about 20 Ma in Naxos (K-Ar, ^{40}Ar/^{39}Ar and Rb-Sr on phengite, Altherr et al., 1982; Wijbrans et al., 1990; Bröcker et al., 2013) or 16 Ma in Ikaria (Beaudoin et al., 2015). Previous studies (Lister et al., 1984; Urai et al., 1990; Gautier and Brun, 1994; Jolivet et al., 1994; Tirel et al., 2009; Jolivet and Brun, 2010; Ring et al., 2010) have shown that Miocene low-angle normal faults have accommodated the late-stage exhumation of the metamorphic core complexes during extension. As a result, several detachments were formed and are now exposed in the northern and western Cyclades, they are the NCDS (North Cycladic Detachment System) and WCDS (West Cycladic Detachment System) (Jolivet et al., 2010; Lecomte et al., 2010; Iglseder et al., 2011; Grasemann et al., 2012). Those structures are associated with top-to-the-NE and top-to-the-SW kinematic indicators, respectively (Fig. 1b). During this period the first formed MCC (Metamorphic Core Complex) were exhumed in the Oligocene and Early Miocene, and they partly escaped from the later (Middle Miocene) complete retrogression and partial melting observed in Naxos, Paros, Mykonos or Ikaria.

2.2. Sifnos Island geology

Sifnos lies in the back-arc region of the Hellenic subduction and is situated in the south-western part of the Aegean Sea between the Serifos metamorphic core complex (Iglseder et al., 2009) and the Milos Quaternary volcano (Fig. 1b). According to Ring et al. (2011), the morphology of Sifnos is partly controlled by NE- and SW-dipping normal faults, and E- or W-dipping younger faults. This island is characterized by an apparently inverse metamorphic gradient within the CBU (Schliestedt and Matthews, 1987; Wijbrans et al., 1993; Lister and Raouzaios, 1996). Indeed, blueschists found at the top of the structural pile are well preserved while the base is strongly retrograded under greenschist-facies conditions. Nevertheless, high-pressure markers are locally preserved in all units on Sifnos (Avigad et al., 1992). Two main tectonics units separated by a shallow-dipping tectonic discontinuity have been recognized (Trotet et al., 2001a): the Cheronissos and the Faros units (Fig. 2). The contact between the two units is named COF (Cheronissos Over Faros) in the following.

Cheronissos Unit (CU) lays on top and it is further divided into three lithologic subunits, which are from top to bottom, 1) the Upper Marble Complex, exposed in the north-western part of the island (mainly calcitic and dolomitic marbles with lenses of quartzites and well preserved blueschists and eclogites), 2) the Eclogite and Blueschist Unit (interbedded quartzites, metabasites, metasediments and acidic gneisses), 3) the Main Marble Unit (a succession of thick marble levels alternating with metasediments and metabasites metamorphosed in the blueschist- to greenschist-facies) (Schliestedt and Matthews, 1987; Wijbrans et al., 1990; Schmädicke and Will, 2003; Ring et al., 2011;Fig. 2). Faros unit (FU) crops out underneath Cheronissos Unit mainly in the south-eastern part of the island (Fig. 2). It is composed of metabasites and metasediments strongly retrograded in the greenschist-facies. Locally, lenses of albite- and epidote-bearing blueschists (AEBS-facies of Evans, 1990) are preserved at the base of Cheronissos Unit and the top of Faros Unit (Trotet et al., 2001a).

Two main stages have been inferred in the metamorphic evolution of Sifnos during the Eocene and Miocene. The first was characterized by HP-LT metamorphism under blueschist- to eclogite-facies conditions possibly due to the subduction of Apulia and the Pindos oceanic basin below Eurasia (Avigad, 1993) in the Eocene with peak conditions around 21kbar and 550 °C (Fig. 3a) (Trotet et al., 2001b; Groppo et al., 2009; Dragovic et al., 2012, 2015; Ashley et al., 2014). In a recent paper, Aravadinou et al. (2015) have related this tectono-metamorphic event (their D1 and D2 stages) to a top-to-the-SE shearing event. This episode has been dated around 45 Ma with different methods such as K-Ar and Rb-Sr on white micas (see compilation on Fig. 3a and b; Altherr et al., 1979; Wijbrans et al., 1990), ^{40}Ar/^{39}Ar apparent age spectra on white micas (Fig. 3a; Forster and Lister, 2005) and Sm-Nd isochrons on garnets (Fig. 3a; Dragovic et al., 2012,2015). The second stage (D3 in Aravadinou et al., 2015) overprinted the blueschist- to eclogite-facies assemblages in the greenschist- to amphibolite-facies; it ranges in age from 30 to 19 Ma based on K-Ar, Rb-Sr and ^{40}Ar/^{39}Ar dating on white micas (Fig. 3a and b; Altherr et al., 1979; Wijbrans et al., 1990; Forster and Lister, 2005; Ring et al., 2011; Bröcker et al., 2013).

2.3. Main geological controversies about Sifnos

One of the main differences of interpretation of the geological evolution of Sifnos relates to the significance of the second stage of deformation and the retrogression of the eclogite- and blueschist-facies parageneses into greenschist-facies assemblages. It has been for instance either interpreted as an extensional episode (Trotet et al., 2001b) or as a contractional episode (Aravadinou et al., 2015). In more details, the nature and origin of the contact between Cheronissos and Faros units, which can be best observed along the road from Apollonia to Vathy (Fig. 2), has been debated in the literature (Avigad, 1990,1993; Wijbrans et al., 1990; Lister and Raouzaios, 1996; Trotet et al., 2001b; Bröcker et al., 2013). This tectonic contact has been diversely interpreted as: a brittle detachment with top-to-the-northeast kinematics (Avigad 1993); a top-to-the-south thrust (Lister and Raouzaios, 1996); a top-to-the-northeast ductile shear zone (Trotet et al., 2001a) and, more recently, as a detachment marked by top-to-the-south brittle-ductile deformation (Ring et al., 2011).

Conventional thermobarometry and multiphase equilibria (Matthews and Schliestedt, 1984; Schliestedt, 1986; Schliestedt and Matthews, 1987; Avigad, 1993; Trotet et al., 2001b; Schmadicke and Will, 2003; Groppo et al., 2009; Dragovic et al., 2012, 2015), oxygen isotope thermometry (Matthews and

Schliestedt, 1984), Zr-in-rutile thermometry (Spear et al., 2006) and quartz inclusion in garnets (Ashley et al., 2014) have been used to estimate the P-T paths and the conditions of peak metamorphism for the Eclogite and Blueschist subunit in Cheronissos Unit (Fig. 3a and c). The shape of the prograde path is similar for all studies and follows a HP-LT gradient inferred from the presence of pseudomorphs of lawsonite (Trotet et al., 2001a). However, the main controversy relates to the retrograde P-T paths in Cheronissos and Faros units. Schmädicke and Will (2003) gave a similar P-T gradient of 10–12 °C/km for both units whereas Trotet et al. (2001b) proposed two different paths with a cooler one for Cheronissos Unit starting from a common peak at around 600 °C and 20kbar (Fig. 3c). Consequently, different explanations were proposed for the apparent inverse metamorphic gradient in Sifnos (eclogites and blueschists rocks overlying greenschists; Altherr et al., 1979; Matthews and Schliestedt, 1984; Schliestedt, 1986; Schliestedt and Matthews, 1987; Trotet et al., 2001b; Wijbrans et al., 1990; Avigad 1993; Groppo et al., 2009; Ring et al., 2011). It was suggested that the greenschist overprint in Faros Unit resulted from pervasive fluid infiltration (Matthews and Schliestedt, 1984; Schliestedt and Matthews, 1987), the Main Marble Unit being a relatively impermeable layer, protecting the Eclogite-Blueschist Unit from it. Wijbrans et al. (1990) assumed instead that overprinting was due to a temperature increase at the base of the metamorphic pile, fitting the younger $^{40}Ar/^{39}Ar$ ages found there (Fig. 3b). Another interpretation suggests that both Cheronissos and Faros units were derived from different structural levels and were juxtaposed next to each other by a thrust during the post-orogenic history (Lister and Raouzaios, 1996), involving a significant displacement between the two units and implying different peaks of metamorphism in the two units. Alternatively, Avigad (1993) and Trotet et al. (2001b), have proposed different cooling histories between the two units with a similar peak of metamorphism, leading to different degrees of retrogression (Fig. 3c). In order to clarify these kinds of discrepancies we focused our field study on the relations between deformation and metamorphism at different scales.

3. A new geological map of Sifnos

Our new geological and structural map at the 1:20,000 scale (Fig. 4) is entirely redrawn following field observations and satellite images analyses. Hence, a more detailed description of the 3D geometry of lithological assemblages and structure, is provided. The new data shed light on the shape of lithological boundaries and on the nature of the contact between Cheronissos and Faros units. The main occurrences of serpentinite and eclogite are reported on the map (Fig. 4). The geometry and kinematics of later normal faults have also been redrawn (Fig. 4). This map is consistent with the more detailed map recently proposed for the northern part of the island by Aravadinou et al. (2015).

3.1. Brittle deformation

The general structure of the island and the topography are controlled by a set of major normal to oblique faults that control the first-order distribution of lithologies on Sifnos (Ring et al., 2011). We carefully remapped these faults that should not be confused with the main contact between Cheronissos and Faros units (Fig. 5a). The largest of these late faults are the Kastro Fault and the Toso Nero Fault respectively along the eastern and western coast of the island, whereas the southern and central parts show a series of SW-dipping normal to oblique faults with different slicken-fibres generations such as the Kamares Fault or the Vathy Fault (see Fig. 4 for location; Fig. 5a and b). In most outcrops, the youngest brittle movement is top-to-the-SW and brittle-ductile criteria also indicate top-to-the-SW motion (Fig. 5c). One of these faults, the Vathy Fault, locally marks the COF (Fig. 5d). This high angle fault crosscuts the contact that is parallel to the regional foliation. The fault shows a core with a thick talc-rich fault gouge and the fault plane shows slickensides (Fig. 5f) and other brittle-ductile criteria indicating top-to-the-SW and −S movements (Fig. 5e and g). A few meters away from the damage zone, the older ductile deformation, characterized by top-to-the-northeast shear is visible like in most of the island. In the far south of Sifnos, S- to SSE-dipping faults occur (Fig. 4). Their exact kinematics is not well established but their effect on the distribution of metamorphic rocks and the associated scarp show a normal component. These faults cut probably the SW-dipping faults.

3.2. Regional foliation

The intense ductile deformation is characterized by well-developed foliations and stretching lineations shown on Fig. 4. Within the same unit, foliation planes are generally parallel to each other in different lithologies. At the scale of the island, in the north, the foliation dips toward the NW, whereas in the rest of the island it

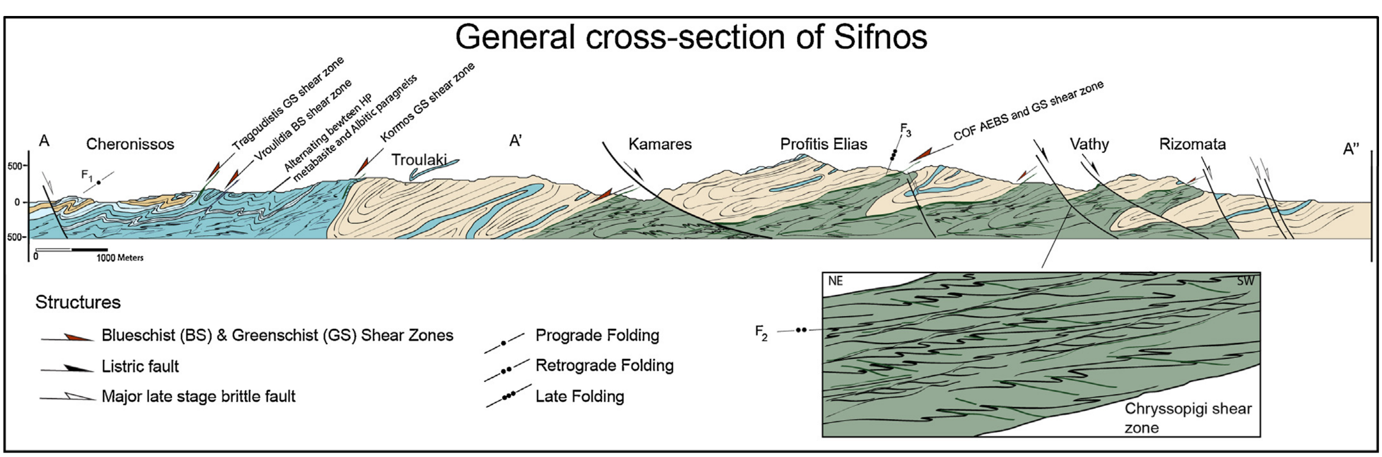

Fig. 4. Geological map of Sifnos.
New stretching lineation map of Sifnos with foliation trajectories. Lithologic contours have been defined on the basis of our field observations and satellite images. We have also included some information of Aravadinou et al., 2015. The major structures are indicated (TNF: Toso Nero Fault; KF: Katro Fault; VF: Vathy Fault; SSEF: S-SE Faults). Lineations associated with blueschist- and greenschist-facies assemblages are respectively indicated in blue and green; arrows indicate the sense of shear (top-to-the-N to −NE in different colours and top-to-the-SW in black). North–south cross-section showing the general architecture of Sifnos and relative sequence of high- and low-angle extensional faults.(For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

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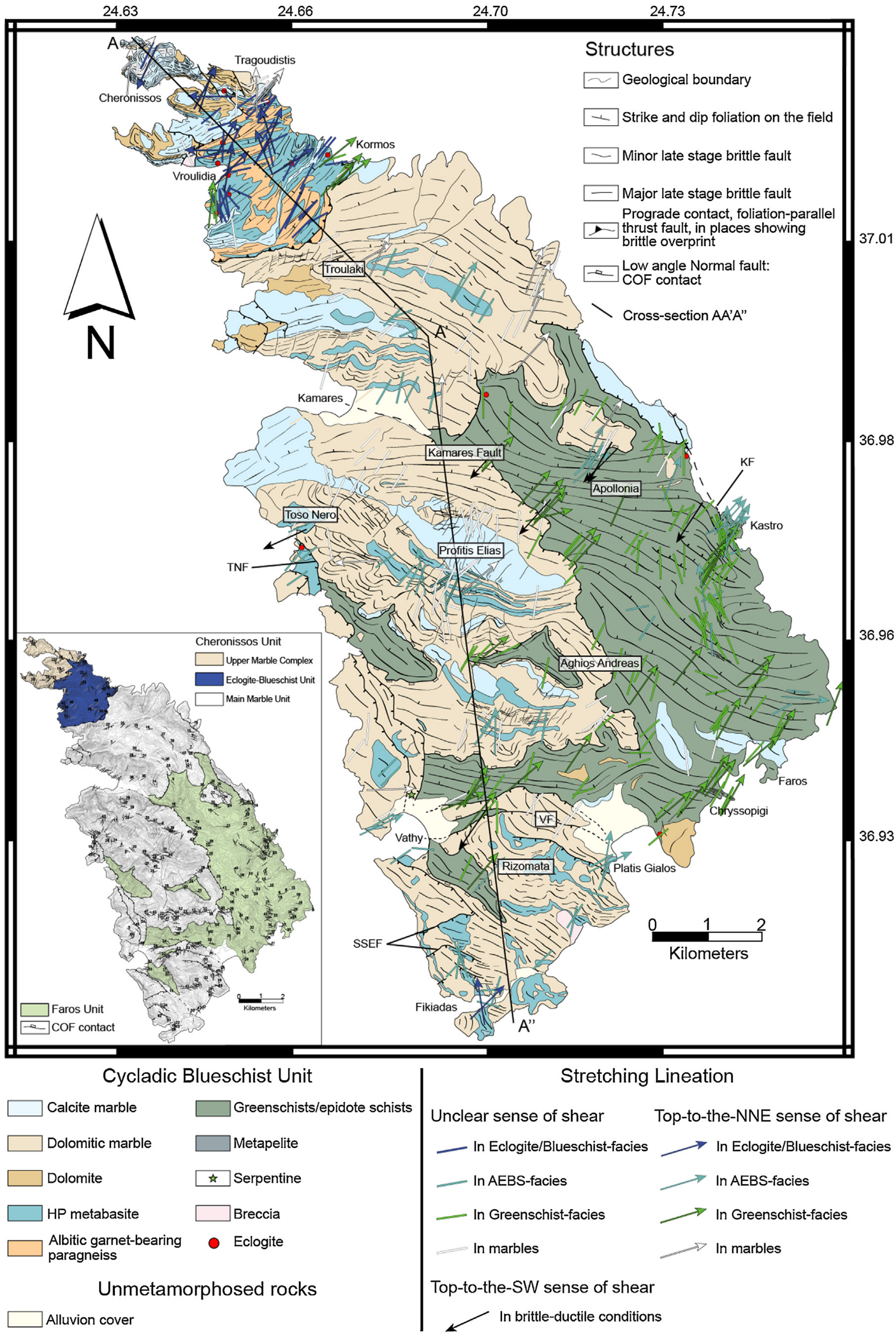

Fig. 4. (*Continued*)

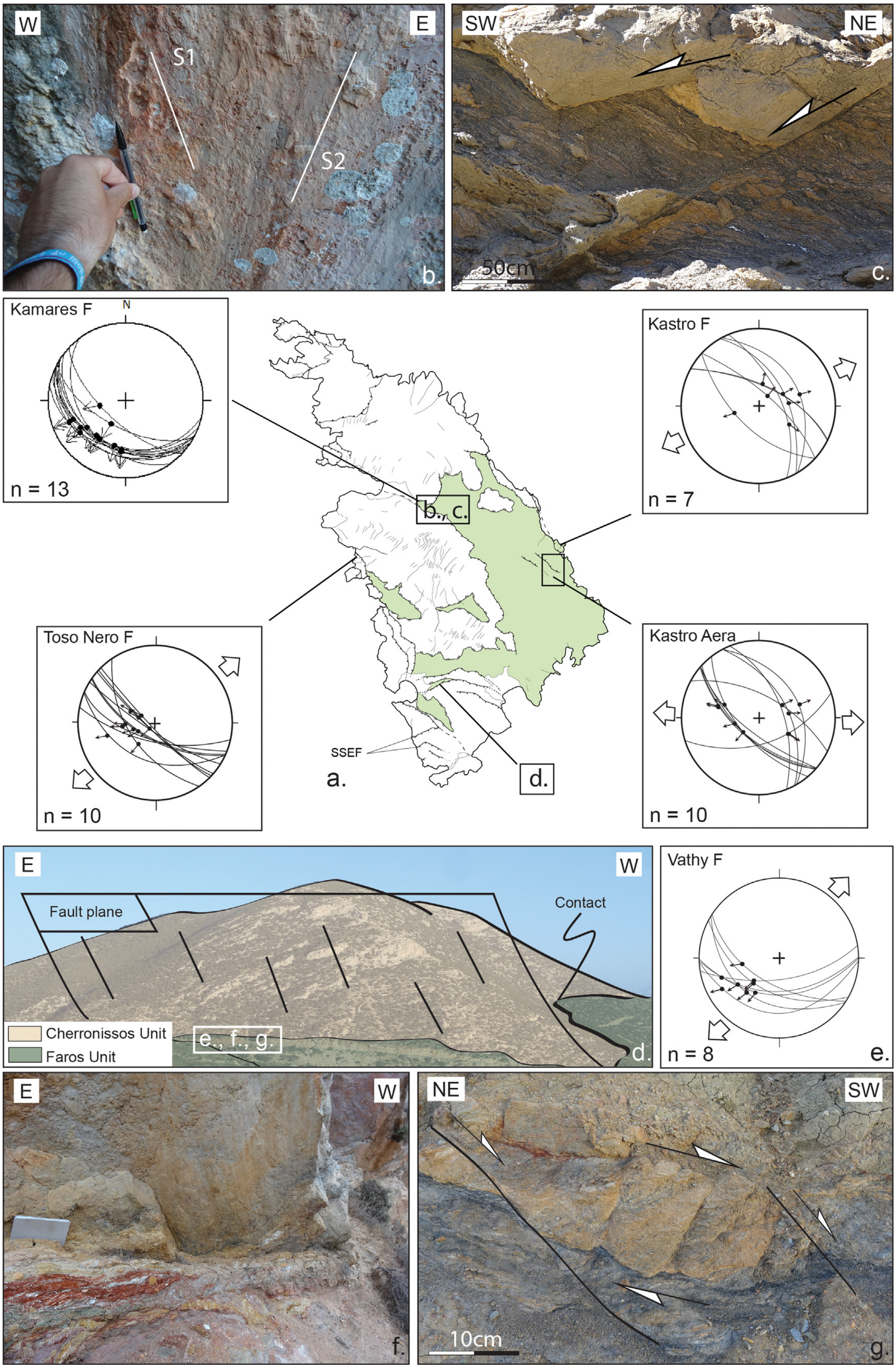

Fig. 5. Brittle deformation on Sifnos.
(a) Location of fault-slip data from high-angle normal faults. The diagrams show great circles of fault planes and the projected trace of slickenside lineations in a lower hemisphere equal-area projection. Arrows indicate extension directions from the measured fault sets (paleostress orientation patterns were calculated with the win-tensor computer-aided inversion software of Delvaux and Sperner, 2003). Readers unfamiliar with the method, or more generally with fault-slip data inversion are referred to the work of Angelier (1990). (b) Kamares Fault showing two slicken-fibre generations. (c) Top-to-the-SW brittle-ductile kinematic indicators associated with Kamares Fault. (d) Vathy SW dipping normal fault with (e) stereographic projections of striations. (f) Fault plane characterized by a few meters thick reddish fault gouge showing (g) top-to-the-SW brittle-ductile kinematic indicators. Note the consistency of the NNE-SSW to E-W direction of brittle extension all over the island.

dips toward the NNE with a large dip range, between 0° and 90° and dip increasing northward (Fig. 6a). Different families of foliation can be distinguished depending on the associated parageneses and the apparent intensity of shearing deformation (e.g. density of shear bands, intensity of stretching. . .). In the northern part of the island, the main foliation (S_2) generally strikes ENE-WSW and dips toward the NNW (Fig. 6a). An early S_1 foliation is seen as relics within garnets porphyroblasts (Trotet et al., 2001a; Aravadinou et al., 2015). In the Main Marble Unit, foliation is generally characterized by NW-SE strike and dips to the NE (Fig. 6a). At the base of Cheronissos Unit, lenses of metabasic rocks wrapped within marbles are preserved at the mesoscopic-scale. Locally, a new AEBS-facies foliation (S_3) is developed, overprinting the earlier foliations (Trotet et al., 2001a; Aravadinou et al., 2015). In Faros Unit, the main foliation (S_3) is well developed with a NNW-SSE strike, dipping toward the NNE. Finally, a later greenschist-facies foliation (S_4) is characterized by a low northward dip at the base of Faros Unit (Trotet et al., 2001a). Hence, from Cheronissos to Faros Unit, a succession of deformation from blueschist- to greenschist-facies conditions is recognized. Moreover, good exposures of the tectonic contact between Cheronissos and Faros Unit show that the foliation planes retain the same strike and dip across the contact and across major lithological contacts as well.

3.3. Stretching lineation

Stretching lineations are widespread through all lithologies and have been distinguished according to the associated mineralogy, dominant metamorphic facies, and/or intensity of deformation. In calcitic and dolomitic marbles, white micas and calcite define the lineation; in basic rocks, the elongation and boudinage of prismatic minerals (glaucophane, epidote, albite and chlorite) reflects a component of stretching, which is also locally expressed within metaconglomerates by elongated pebbles carrying pressure shadows. These lineations are projected on the map of Fig. 4. At the scale of the island and on most outcrops, stretching lineations trend consistently NE-SW (Fig. 6b), except for some local NNW-SSE-trending lineations observed in the northern part of the island (see also Aravadinou et al., 2015). The plunge of lineation is generally shallow and it rarely exceeds 40°. We have distinguished three successive generations of lineations based on the metamorphic grade coeval with deformation: 1) under blueschist-facies conditions, the trend of lineations, defined by glaucophane in most cases, shows a dispersion between N330°E and N30°E with an average around N350°E (Fig. 6b); 2) in Faros Unit, the lineation characterized by albite and chlorite, is less dispersed with an average around of N52°E (Fig. 6b); 3) close to the main contact, in AEBS-facies conditions, lineations defined by epidote, albite and rare glaucophane, trend in average around N30°E (which correspond to the average of the trend of blueschist and greenschist lineation, see stretching lineation on the map in Fig. 4).

3.4. Fold directions

Three folding events have been identified in the field. In the structurally highest and northern part of the island, early isoclinal to very tight macroscopic folds F_1 can be seen to affect thick massive dolomites alternating with calcitic marbles (Figs 7b and 7; see also Aravadinou et al., 2015). These folds are asymmetric and generally south-vergent, with an axial plane parallel to the foliation. The geometry and kinematic interpretation of these folds is detailed in Section 6. A second generation of folds F_2 is particularly well developed at small scale in both units and generally associated with an intense shearing deformation. F_2 folding is dominantly NE-vergent but characterized by variable axial trend with respect to the lineation. The axial plane of the first family is lying parallel to the foliation with the fold axis sub-parallel to the local stretching lineations. The tight to isoclinal folds are overturned toward the N or NE. These folds are mainly observed in areas where the deformation is intense such as near Vroulidia (northern part of the island, Fig. 7d) or Chryssopigi (southeast part of the island, Fig. 7e). They are best expressed in metabasites and metapelites. The second set has its axial planes dipping toward the north and the axes are roughly perpendicular to the lineation (Fig. 7f). These folds have been observed at small scale in all units. Finally, late stage F_3 folds refold the main foliation and tectonic contacts with an orientation perpendicular to the second generation. The relation between F_1, F_2, F_3 folds and the top-to-the-north or −northeast shearing deformation is discussed in Section 6.

4. Kinematic indicators and metamorphic conditions within Cheronissos Unit (CU)

4.1. Eclogite-Blueschist subunit

This unit, which outcrops in the northern part (Fig. 4), is composed by mafic and siliceous rocks. Most kinematic indicators are top-to-the-N to −NE. All lithologies are affected by asymmetric structures at various scales: 1) Decametric asymmetric folds affect the main foliation either in mafic (Fig. 8a) or in siliceous layers (e.g., quartz and phengite aggregates in Fig. 8b); 2) Meter-scale asymmetric boudinage of mafic (eclogite) layers embedded in a weaker matrix indicating a top-to-the-northeast shear sense (Fig. 8c); 3) Shear bands in all units (Fig. 8d and e). Spacing between shear bands ranges from a few millimetres to a few centimetres in the weakest levels. The angle between shear bands and foliation varies from one outcrop to another, depending on lithology. Shear bands are commonly marked by thin glaucophane coatings in mafic rocks (Fig. 8f) and quartz/mica in acidic rocks. Shear bands give rise to sigmoidal foliation at the centimetric or metric scale compatible with top-to-the-northeast sense of shear; 4) Pressure shadows within garnet porphyroblasts consisting of quartz, mica, rare glaucophane and chlorite also indicate a top-to-the-NE sense of shear (Fig. 8g and h).

4.2. Upper Marble Complex subunit and Main Marble subunit

The marbles and schist lenses composing the Upper Marble Complex and the Main Marble units display kinematic indicators showing a top-to-the-northeast sense of shear (Fig. 4) consistent with the structures described in the Eclogite-Blueschist Unit, but with a more localized distribution. In marbles, stretching is expressed by boudinage at various scales. In the northern part of the island for instance, competence contrast between calcite and dolomite results in domino and asymmetrical sigma/delta clasts indicating a top-to-the-northeast shear sense (Fig. 9b and c). Stretching is also marked by tension gashes and calcite recrystallization within marbles (Fig. 9d). Isoclinal folds overturned toward the north, with an axis generally perpendicular to the stretching lineation, are commonly observed in the Main Marble Unit (Fig. 9e). Few kinematics indicators are observed in other lithologies in these two subunits of Cheronissos Unit. They all indicate a top-to-the-northeast sense of shear (e.g., asymmetric shape of stretched carbonate pebbles in metaconglomerate layers in Fig. 9f).

4.3. Metamorphic conditions of shearing deformation in Cheronissos Unit

In the northern part of the island, Upper Marble Complex and Eclogite-Blueschist Unit are characterized by an overall good preservation of HP-LT parageneses such as fresh and very abundant glaucophane and omphacite within metabasites. Shear bands and sometimes strain shadows around garnets are often filled with

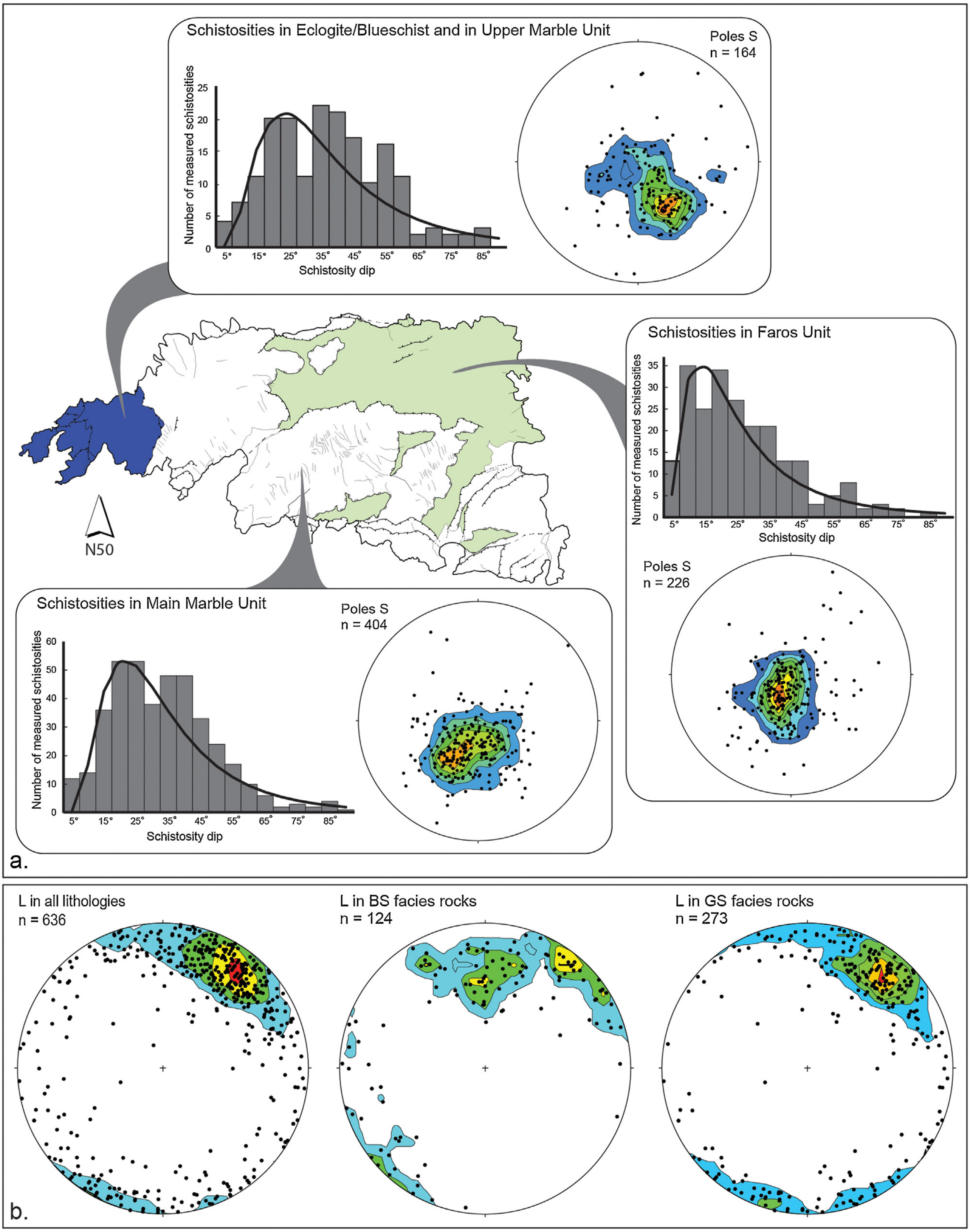

Fig. 6. Main planar fabrics and stretching lineation.
(a) Statistics of the main foliation of different units showing distribution frequency of dip schistosity and Schmidt's lower hemisphere equal-area projection of schistosity poles. (b) Statistics of the preferred orientation of stretching lineation presented in Schmidt's lower hemisphere equal-area projection. We used the 1% area contouring to define the contour lines. In our case, we used a contour interval value of 2.

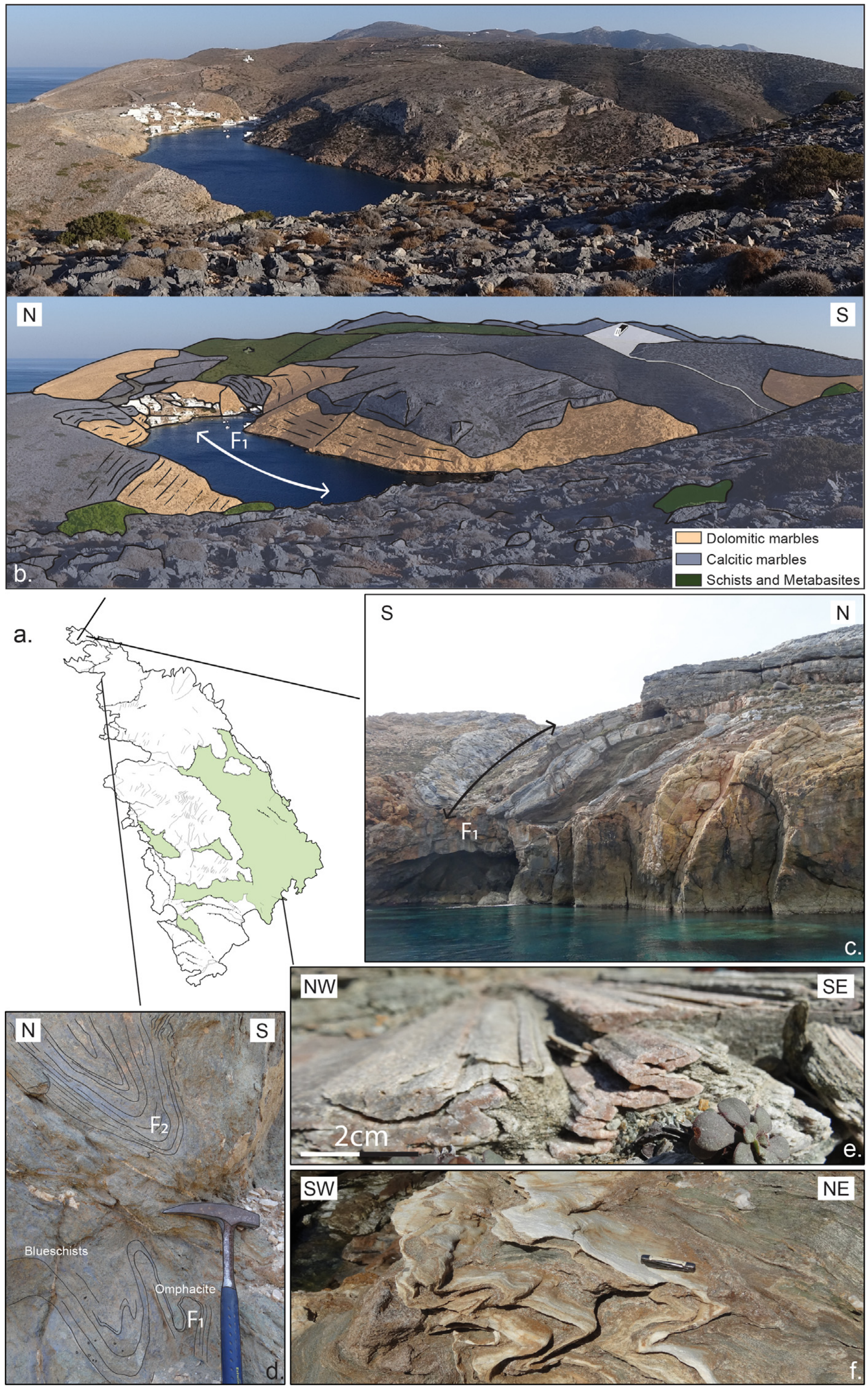

Fig. 7. Different folding phases at various scales.
(a) Location of field photographs. (b) and (c) show field evidences of folding of dolomitic marbles and calcitic marbles in the northern part of the island. (d) Syn-blueschist folding affected early folds in a metabasite. Note that F_2 fold axes are mostly perpendicular to the stretching direction. Two sets of axial planes showing, (e) axes parallel to the stretching and (f) perpendicular to the stretching lineation in the south-eastern part of the island.

glaucophane and phengites, indicating syn-HP-LT conditions for the top-to-the-N to −NE shearing deformation (blue arrows on Fig. 4). In the Main Marble Unit, HP-LT parageneses are generally more retrograded when approaching the contact between Cheronissos and Faros units. In this latter unit, top-to-the-northeast kinematic indicators in metabasite lenses are associated with glaucophane, epidote, phengite and sometimes chlorite, albite characteristic of AEBS-facies P-T conditions (green/blue arrows on Fig. 4).

5. Kinematic indicators and metamorphic conditions within Faros unit

5.1. Top-to-the-NE ductile shear deformation

Top-to-the-northeast kinematic indicators are widely distributed through Faros Unit but more common in zones of strain localization. Several types of shear-derived objects are observed: 1) metric shear bands indicating top-to-the-northeast sense of shear

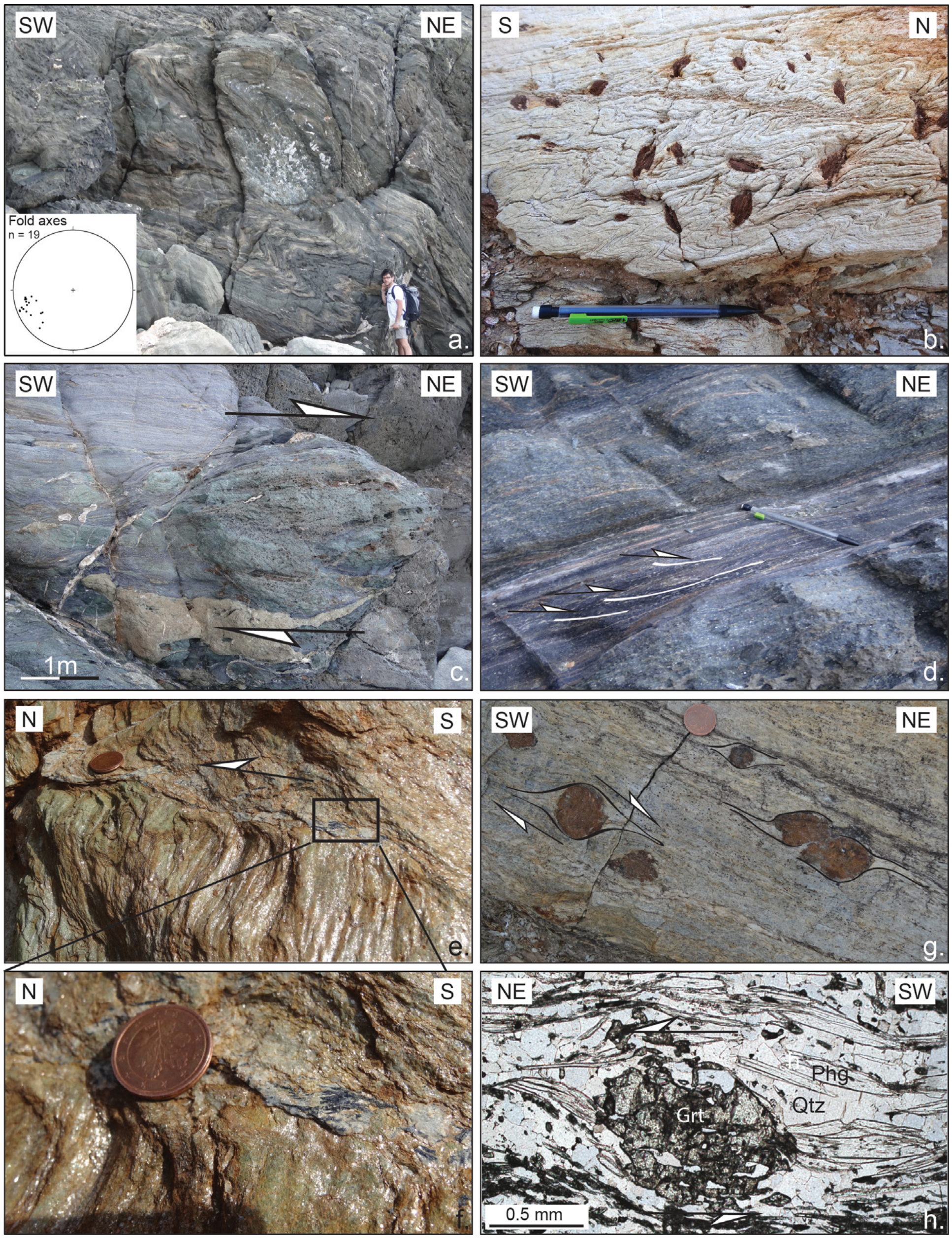

Fig. 8. Microstructures and macrostructures observed in Sifnos Eclogite-Blueschist Unit.
(a) Decametric asymmetric folds in mafic rocks close to Kormos, showing axes mostly perpendicular to the stretching direction. (b) Asymmetric folds in siliceous levels with S_1 preserved in garnets in the upper level of Eclogite-Blueschist Unit. (c) Boudinage of eclogites showing a top-to-the-NE sense of shear. (d) Top-to-the-NE shear bands affecting competent mafic rocks and (e) acidic rocks in the north of the island. (f) Details of shear bands marked by glaucophane in more acidic rocks. (g) Pressure shadow on garnet porphyroblasts in a field photograph and (h) thin section. They show top-to-the-NE sense of shear close to the contact between Eclogite-Blueschist Unit and Main Marble Unit.

near Kamares Fault (Fig. 10b); 2) asymmetric boudins of competent lithologies, such as those preserving mafic eclogite boudins (Fig. 10c); 3) sheared quartz-carbonate veins perpendicular or parallel to the main foliation showing pressure shadows filled with chlorite and albite such as near Vathy, with NE-verging shearing in greenschist-facies conditions (Fig. 10d and e); 4) syn-greenschist asymmetric folding affecting layers rich in glaucophane and epidote close to the COF (Fig. 10f). Crenulation of an earlier foliation compatible with top-to-the-northeast shearing is also frequent within Faros Unit and especially near zones of strain localization such as Chryssopigi (Fig. 10g).

Greenschist-facies ductile deformation is more localized in Faros Unit than in other units along shear zones. One spectacular example of such shear zones can be observed at the southern coast of the island (Fig. 11a). This area, located near the base of Faros Unit, shows a distinct gradient of shearing deformation. In average, the foliation strikes almost E-W and dips moderately toward the southwest. The shear zone develops within micaschists and minor marbles, displays the same overall distributed top-to-the-NE kinematic indicators occurring at various scales over the whole Faros Unit. Such kinematic indicators are also exposed near the port of Faros. The N50°E trending stretching lineation is marked by stretched micas and albite pods. The deformation strongly increases toward the northwest and the gradient is clearly visible on Chryssopigi peninsula (Fig. 11a). Approaching the peninsula, an increasing number of veins composed of quartz, chlorite, and carbonates are sheared and transposed into the main foliation (Fig. 11c). The foliation and the veins are strongly and asymmetri-

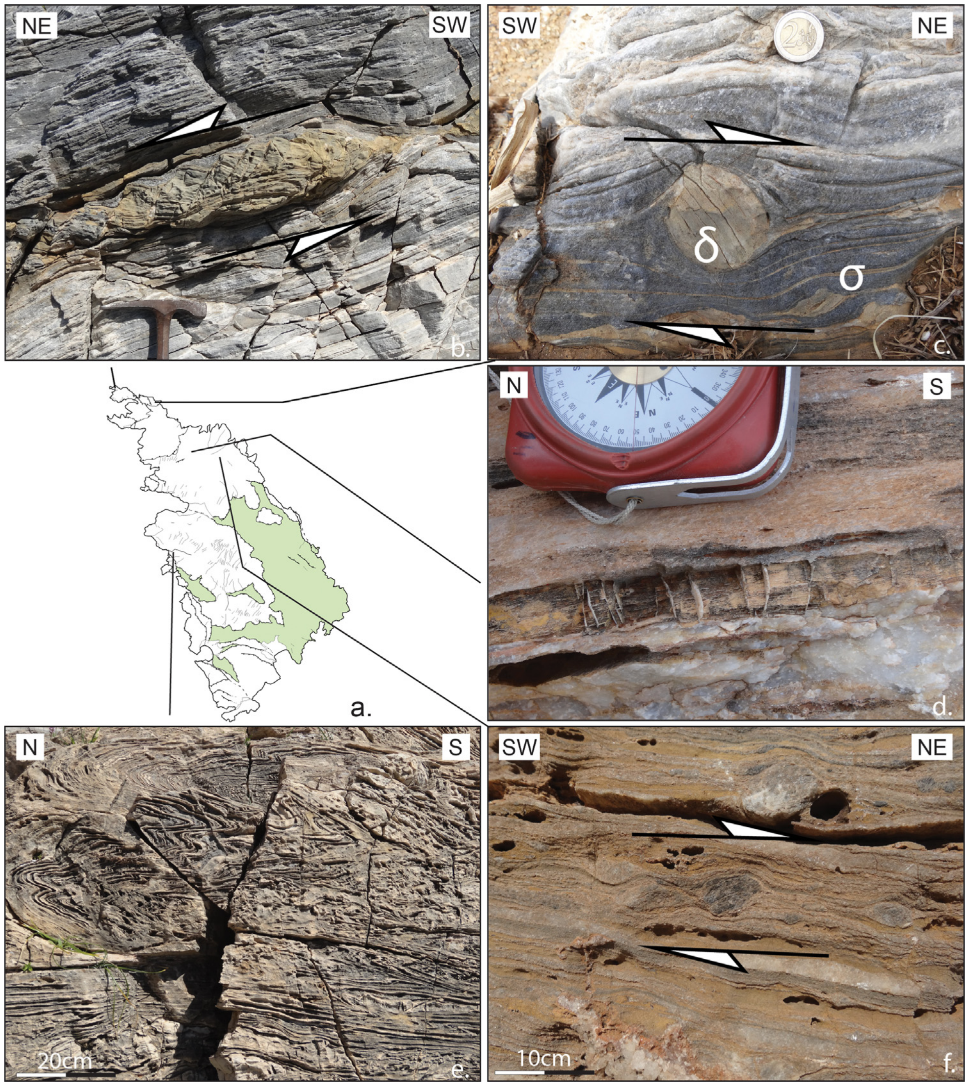

Fig. 9. Microstructures and macrostructures observed in Upper Marble Complex and Main Marble Unit.
(a) Location of field photographs. (b) Difference of competence between calcite and dolomite showing the development of dominos and (c) delta/sigma clasts indicating top-to-the-NE sense of shear. (d) North-south stretching shown by calcite recrystallization within tension gashes. (e) Centimetric folds showing axes mostly perpendicular to the stretching direction. (f) Top-to-the-NE shear sense defined by the asymmetric shape of stretched carbonate pebbles in metaconglomerate layers.

cally folded consistently with the mean shearing direction. Curved fold axes are dispersed around a direction perpendicular to the stretching lineation (Fig. 11a, number 1). Here, an axial plane crenulation cleavage develops in the hinge of these folds (Fig. 11d). Sheared lenses of metabasite, or quartz and calcite veins indicate a top-to-the-northeast sense of shear (Fig. 11e). Toward the top of the peninsula, moving upward toward the core of the shear zone, the non-coaxial deformation increases sharply. Fold axes tend to progressively rotate toward the shearing direction and are finally deflected parallel to the stretching lineation, although no clear closed eye-structure has been observed in the YZ plane (Fig. 11g). These folds are typically a-folds that show a large simple shear component in the direction of the stretching lineation (Fig. 11a, number 3). In the most deformed areas, observations of the XZ plane of the finite strain ellipsoid show a dense network of small-scale shear bands, all compatible with top-to-the-northeast sense of shear (Fig. 11f). Their spacing ranges from a few millimetres to a few centimetres and they are associated with white mica and albite. Chlorite, calcite and quartz veins are stretched and folded and totally transposed into the foliation.

5.2. Metamorphic conditions of the top-to-the-northeast deformation

In the Faros unit, metabasites that are deformed by top-to-the-NE deformation show strongly retrograded blueschist- or greenschist-facies rocks. From top to bottom 1) eclogite and blueschist lenses are locally preserved close to the COF in the northern part of the island (Fig. 10c). At macro-structural scale, the dominant paragenesis is characterized by glaucophane, epidote, phengite and albite. In this structural level, glaucophane filling of top-to-the-NE shear bands indicates that deformation has partly acted in HP-LT conditions (see Fig. 12); 2) in the middle part of Faros Unit, deformation is locally more intense and the retrogression into greenschist-facies more advanced. Chlorite-filled pressure shadows develop around quartz-calcite lenses, attesting that top-to-the-northeast deformation has also acted in greenschist-facies conditions (Fig. 10e). We have furthermore observed top-to-the-northeast shear bands filled by low-grade minerals such as chlorite and albite, leading to the same conclusion; 3) the base of Faros Unit is the most retrograded zone (e.g., Chryssopigi). Here, veins filled by calcite, chlorite and albite are mostly (or totally) trans-

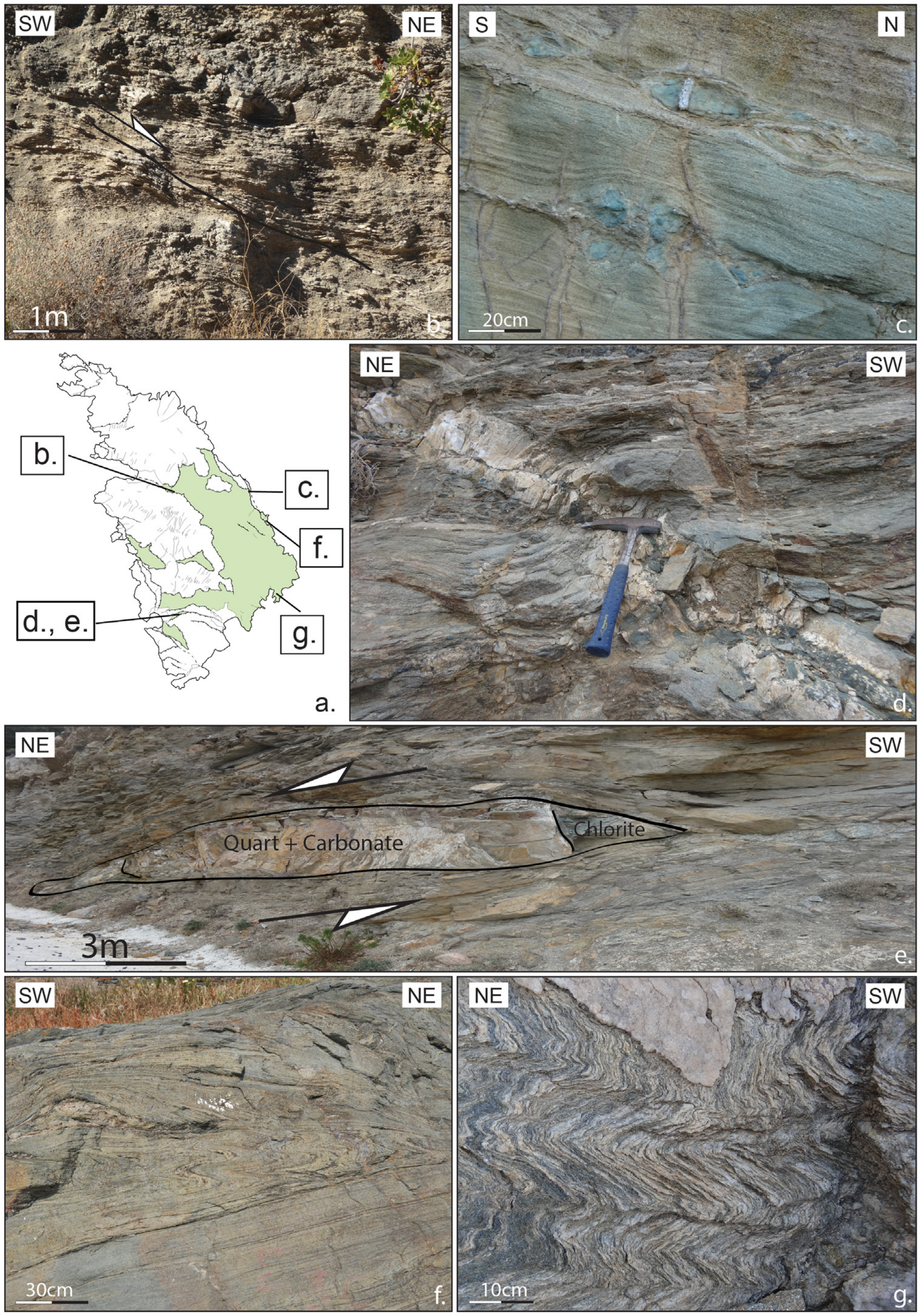

Fig. 10. Macrostructures observed in Faros Unit (FU).
(a) Location of field photographs. (b) S-C Structures with top-to-the-NE sense of shear characterized by metric shear bands in a metapelite. (c) Asymmetric mafic eclogite boudins cross cut by quartz-carbonate veins showing a north-south stretching. (d) Sheared quartz-carbonate veins cross cut the main foliation and (e) are commonly transposed in the foliation with pressure shadows filled in chlorite and albite showing top-to-the-NE sense of shear. (f) Centimetric folds showing axes mostly perpendicular to the stretching direction. (g) Axial plane crenulation cleavage associated with the hinge of folds at the base of this unit.

posed in the main foliation. At the micro-structural scale, in thin sections collected from Chryssopigi, shearing deformation is localized around syn-kinematic porphyroblasts of albite that are surrounded by quartz-mica strain shadows. These criteria attest that top-to-northeast deformation has acted during a continuum from blueschist- to greenschist-facies conditions during exhumation.

6. Kinematics of deformation in the main shear zones

6.1. Contact between Cheronissos and Faros units (COF)

The COF contact, as shown on the cross-section (Fig. 4), is folded by open folds and then later faulted by high-angle faults. This contact appears sub-parallel (or only locally slightly discordant) to

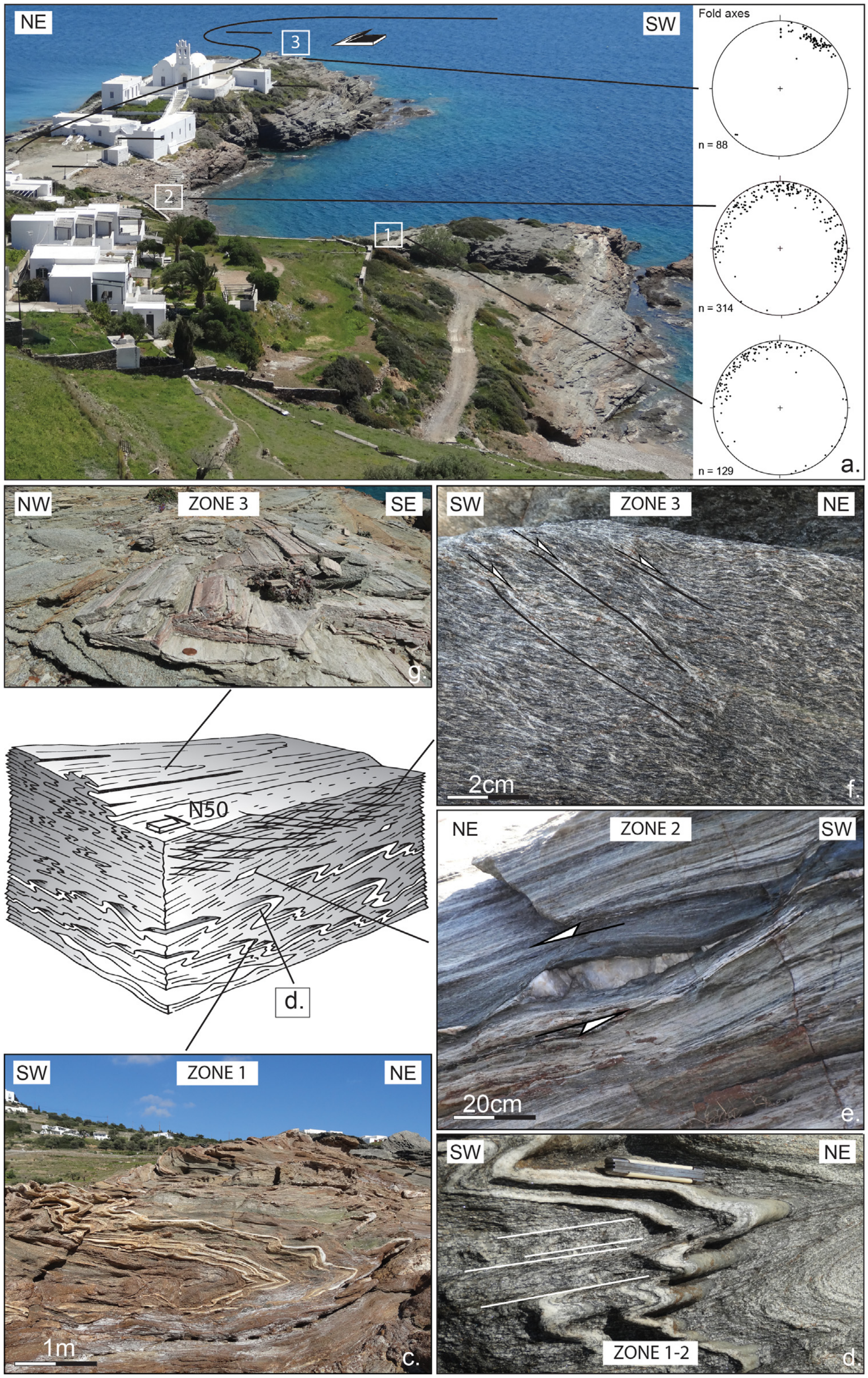

Fig. 11. Chryssopigi shear zone defined by a distinct gradient of shearing deformation.
(a) Large scale representative view of the Chryssopigi shear zone in the south-eastern part of the island. Albite pods marked the stretching lineation trending N50°E. All information is summarized with synthetic 3-D diagrams. This shear zone is divided in three areas; zone 1 corresponds to (c) an intense folding and (a) associated Schmidt's lower hemisphere equal-area projections showing fold axes dispersion; zone 2 is defined by (d) axial plane crenulation cleavage associated with the hinge of folds. (a) Fold axes tend to progressively rotate toward the shearing direction. (e) Sheared lenses of quartz and calcite showing a top-to-the-NE sense of shear; zone 3 is marked by intense non-coaxial shearing consistent with an overall top-to-the-NE kinematics. (f) Shear bands spacing ranges from few millimetres and (g) a-folds are commonly observed. Note that folds axes are now parallel to the stretching direction.

the main foliation. It is particularly well exposed in the southern part of the island along the country road that brings from Vathy to Fikiadas beach (Fig. 4). This area shows a distinct gradient of shearing deformation close to the main contact with the Cheronissos Unit and a shallow northeast-dipping foliation, sometimes strongly folded (Fig. 12d). There, sheared carbonate pebbles and

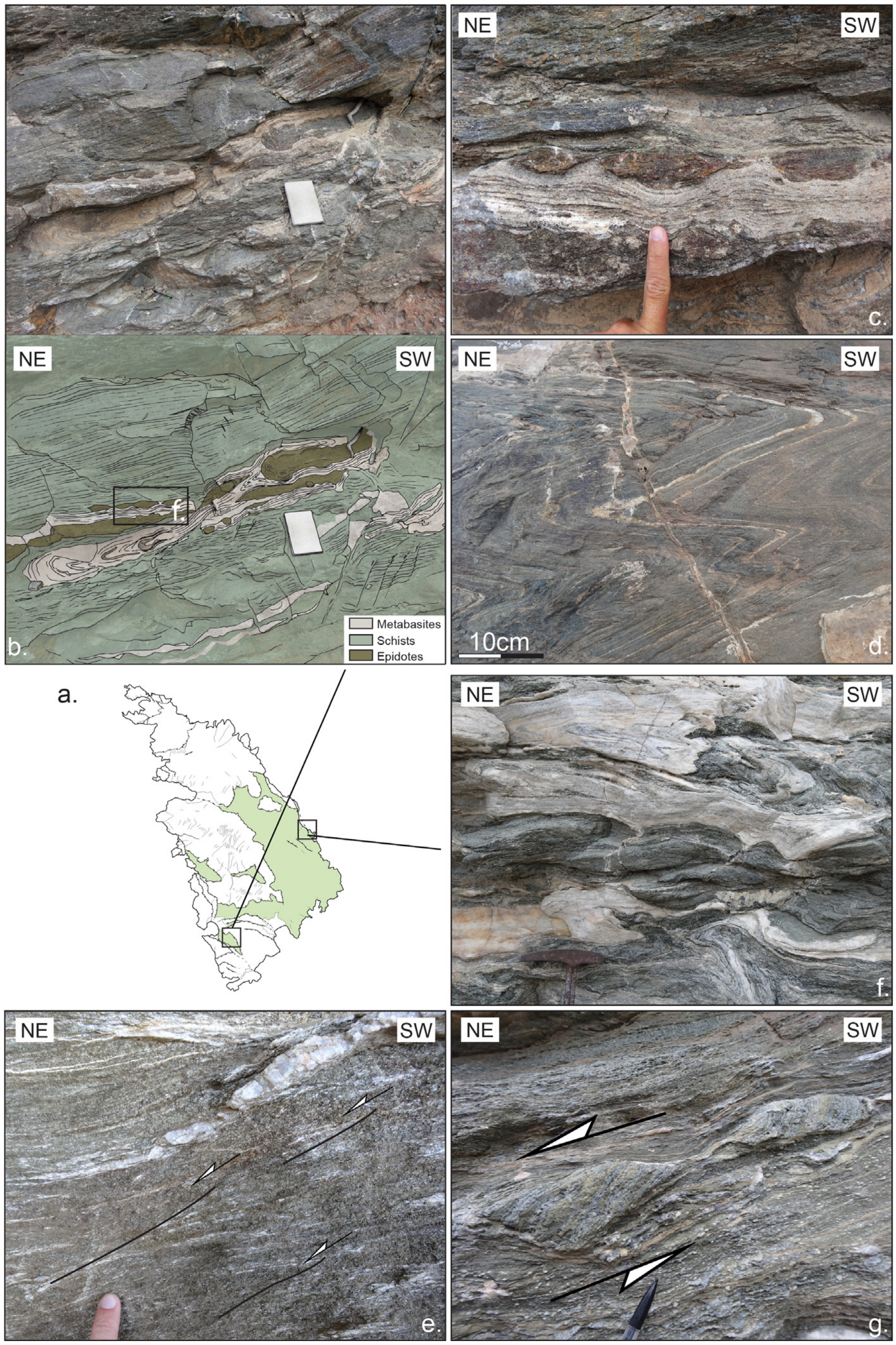

Fig. 12. COF contact.
The COF contact is well exposed (a) Intense ductile deformation shown by folding in all lithologies. Top-to-the-NE shear bands associated with glaucophane affect the foliation. (b) Asymmetric boudinage of epidotite boudins showing a top-to-the-NE shear sense. (c) Closely-spaced shear bands associated with white mica indicate top-to-the-NE sense of shear close to Vathy. (d) Similar features observed close to Kastro, just below the main contact.

asymmetric boudinage of epidotite boudins indicate a top-to-the-northeast shear sense (Fig. 12b and c) together with closely spaced shear bands associated with glaucophane and white micas. The NE-trending stretching lineation is defined by the elongation of albite spots and glaucophane needles.

The same features are observed close to Kastro, just below the main contact with the upper unit (Fig. 4). In this area the foliation strikes almost N-S and dips shallowly toward the east. The lineation is marked by epidote, glaucophane and albite. Numerous quartz lenses are transposed in the foliation and in shear bands with an asymmetry compatible with a top-to-the-northeast sense of shear (Fig. 12e and f). Asymmetric boudinage of epidotites is also well developed and indicates a top-to-the-northeast shear sense (Fig. 12g). Late veins, perpendicular to the regional stretching, filled with chlorite, quartz and hematite cutting the main foliation, suggest a continuum of stretching during more brittle conditions in greenschist-facies conditions. To summarize, the COF contact is characterized by a more intense shearing deformation and the sense of shear is clearly top-to-the-northeast, as observed within Cheronissos and Faros units. This shearing has been active during the retrogression from blueschist- to greenschist-facies conditions.

6.2. Shear zones away from the COF contact

The Eclogite-Blueschist Unit overlays the Main Marble Unit and the contact is exposed along the east coast close to Troulaki (see location on Fig. 4). The average dip of foliation is about 50°W (Fig. 13a). The stretching direction is provided by the mineral lineation (glaucophane, chlorite, albite and calcite) and the elongation of pebbles within metaconglomerate layers interleaved with metabasites and marbles. Depending on the mineral paragenesis, the trend of lineations changes from N70–80°E for the more retrograded levels to N45°E for the better-preserved blueschist-facies. In particular close to the Main Marble Unit, a metric metaconglomerate level, which mainly contains calcitic and dolomitic pebbles, shows near its base eclogite pebbles when approaching the Eclogite-Blueschist Unit (Fig. 13c). Immediately above, a pile of fully retrograded metabasites crops out (Fig. 13d). Associated with greenschist-facies parageneses, quartz veins parallel or perpendicular to the main foliation are observed (Fig. 13e). Well preserved eclogite- and blueschist-facies parageneses with pristine garnets occur just above (Fig. 13g). Kinematic indicators such as domino structures (Fig. 13b), stretched pebbles in metaconglomerates (Fig. 13c), shear bands (Fig. 13f) and asymmetrical eclogite boudins (Fig. 13g), are common in all units at all metamorphic grades and are characterized by a top-to-the-NE to –E sense of shear.

In the north-eastern part of the island, close to Cheronissos (Fig. 4), the contact between Upper Marble Complex and Eclogite-Blueschist Unit is well exposed along the coast. This contact appears similar to the previous one except for the absence of metaconglomerate level. Kinematic indicators are top-to-the-northeast in both units and the degree of retrogression seems to be the same as in the contact described above.

7. Discussion

7.1. Timing of deformation and metamorphism

Based on kinematic indicators and their relations with metamorphic parageneses described above and those reported in the literature, we propose a new metamorphic map (Fig. 14). This map is intended to display the first-order distribution of the dominant parageneses as seen in the field, keeping in mind that the peak of metamorphism was everywhere in similar P-T conditions, in the eclogite-facies. In this section, we re-evaluate the chronological evidence used to support the relative timing of tectonic and metamorphic events recorded on Sifnos.

Throughout most of Cheronissos Unit, HP-LT parageneses are particularly well preserved. In the northern part of the island, syn-kinematic minerals in shear band and pressure shadows are developed during syn-orogenic deformation. Locally, an early S_1 foliation has been observed as relics into garnet porphyroblasts but kinematic indicators related to this event are unknown. Most kinematic indicators associated with the retrograde path (under HP-LT conditions) are distributed heterogeneously in all lithologies and indicate a penetrative top-to-the-N shear sense in the upper part and top-to-the-NE to –E in the rest of this unit. Aravadinou et al. (2015) have recognized top-to-the-SE kinematic indicators in thin-sections cut in zones preserved from the bulk of retrograde deformation in northern Sifnos. If one admits that the original stretching direction has been preserved in these zones, the shear sense during the beginning of S_2 formation was top-to-the-SE. This is debatable because the folds refolding S_2 are acute and it is not sure whether the original direction of stretching direction was preserved but this is the only available information in favour of a top-SE shearing event, which could represent the early shearing related to thrusting near the peak of pressure, as proposed by Aravadinou et al. (2015), before the top-to-the-NE shearing. This second-stage shearing is instead observed all over the island and it started before the rocks had left the blueschist-facies during their exhumation. It is possible that this change of shear sense corresponds to the transition from burial to exhumation at high pressure.

Ductile deformation is locally more intense in certain areas such as in the northern part of the island at Vroulidia. This pervasive deformation is linked with the exhumation of Cheronissos Unit from its maximum burial depth and is dated around 45 Ma (Altherr et al., 1979; Wijbrans et al., 1990; Forster and Lister, 2005; Dragovic et al., 2015). At the base of Cheronissos Unit and top of Faros Unit, close to the main contact, a strong deformation gradient in AEBS-facies P-T conditions is observed near Kastro and close to Rizomata Mountain (Fig. 12). Greenschist-facies conditions are recorded in the whole Faros Unit and locally also in Cheronissos Unit close to tectonic contacts (Fig. 14), and are always associated with top-to-the-NE or –E kinematic indicators. Strain localization in Faros Unit is systematically associated with greenschist-facies conditions such as near Chryssopigi (Fig. 11). Available radiochronological data (Altherr et al., 1979; Wijbrans et al., 1990; Ring et al., 2011; Bröcker et al., 2013), obtained on rocks sampled in Faros Unit, date the greenschist-facies retrogression from the Oligocene and Miocene like on most other islands of the Cyclades (e.g., Syros Island, Maluski et al., 1987; Baldwin, 1996; Wijbrans et al., 1990; Tinos and Andros Islands, Bröcker et al., 1993; Huet, 2010).

All lithologies are affected by early isoclinal folds F_1, overturned to the SW Figs. 4 and 7b) and particularly well expressed by alternating folded calcitic and dolomitic marbles in the northern part of the island, where HP rocks are best preserved. The relation between F_1 folds and the top-to-the-north to –northeast shear deformation is debated. Avigad (1990) suggested that they were formed before the peak of metamorphism in the orogenic wedge (or subduction channel) during the subduction of the African slab involving ductile kinematic indicators top-to-the-SW, hence their overturning to the SW. Alternatively, they may have formed continuously during exhumation from blueschist- to greenschist-facies conditions during the dominant top-to-the-northeast shearing and their overturning to the SW is only apparent. Based on field observations (e.g., relationships between dolomitic marbles and marbles), we suggest that the metamorphic pile of Sifnos underwent important flattening and shearing before the peak of metamorphism. This folding could be associated with top-to-the-south deformation that was active within the subduction zone, in syn-orogenic conditions (Huet et al., 2009; Philippon et al., 2011; Aravadinou et al., 2015). The excellent preservation of eclogite- and blueschist-facies parageneses in the north of Cheronissos Unit suggests that these folds started to form within HP-LT conditions and evolved continuously during exhumation from blueschist- to greenschist-facies conditions during the dominant top-to-the-northeast shearing. A later fold generation F_3 deforms the COF contact where we have observed a certain localization of greenschist-facies deformation.

7.2. P-T-time paths of Sifnos and links to deformation

Our study shows that the intense greenschist retrogression of Faros Unit is closely associated with the deformation along the main tectonic contact between Cheronissos and Faros Unit during exhumation. Conspicuous preservation of HP-LT parageneses in Cheronissos Unit largely reflects the fact that greenschist-facies deformation localized in deeper parts of CBU and only locally affected this unit. Thus, Cheronissos Unit was already partly exhumed while Faros Unit was exhuming below it. The observation that the lower part of Faros Unit is dominated by low-pressure parageneses suggests that deformation progressively migrated downward during exhumation. The P-T estimates of Trotet et al.

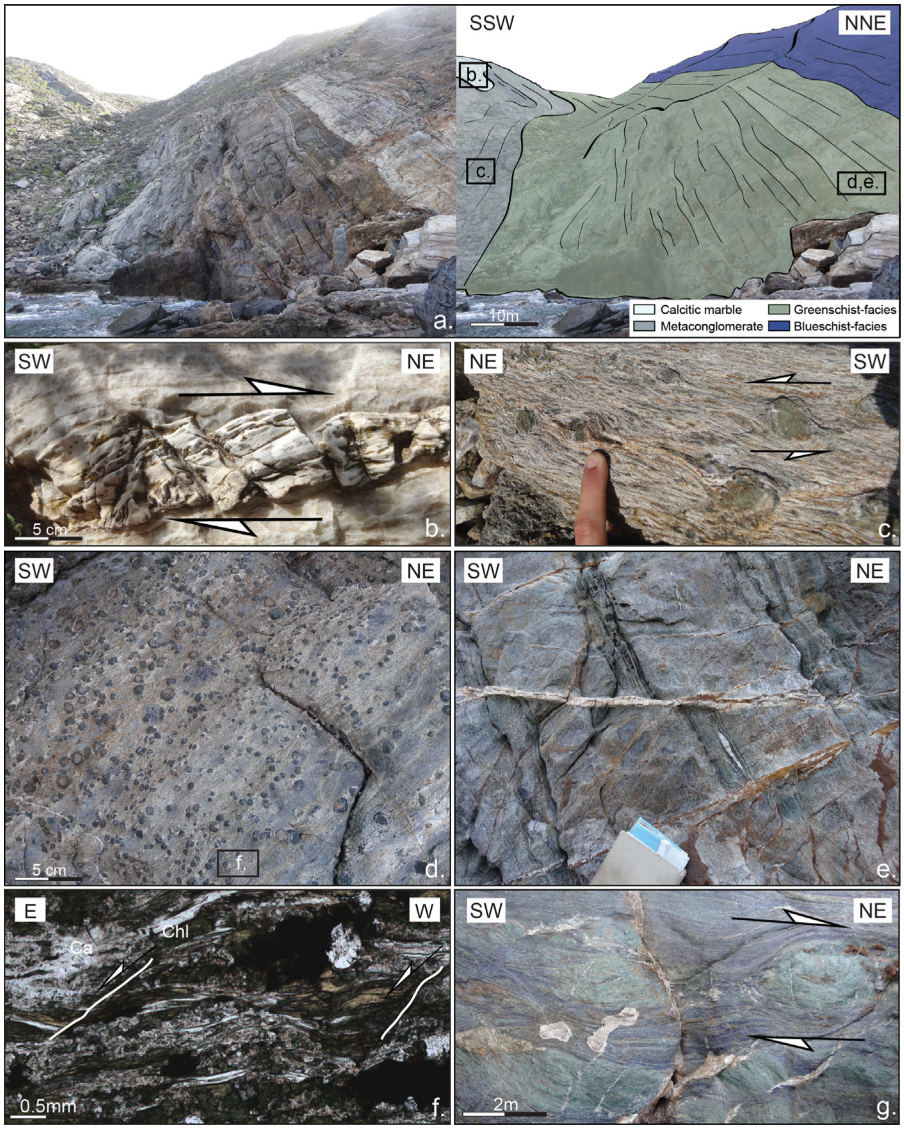

Fig. 13. Contact between the Eclogite-Blueschist Unit and Main Marble Unit (a) This contact is characterized by an average dip of the foliation is about 50° westward and showing a local greenschist-facies retrogression. All kinematic indicators indicate top-to-the-NE sense of shear. Bottom to top, (b) dominos structures in marbles and (c) asymmetric metabasite pebbles within a metaconglomerate level showing a top-to-the-NE sense of shear. (d) Metabasite fully retrograded in the greenschist-facies conditions is associated with (e) quartz-calcite veins which are parallel or perpendicular to the foliation. At micro scale, (f) millimetric shear bands filled in chlorite showing a consistent top-to-the-NE to −E sense of shear. (g) Metabasites form asymmetric pinch boudinage indicating top-to-the-NE kinematics in blueschist-facies condition.

(2001a,b) plot at slightly higher temperature (around 600 °C) than those of Groppo et al. (2009), whose peak is around 560 °C (Fig. 3c). Whether this discrepancy is due to different sampling strategies or to different petrological approaches is beyond the scope of this paper. However, the higher temperature proposed by Trotet et al. (2001b) for the greenschist-facies conditions fits quite well the HT pulse proposed around 19 Ma by Wijbrans et al. (1990) based on ^{40}Ar/^{39}Ar data on phengite in Faros Unit (see ages in Fig. 3a and b). Further petrological and chronological studies are needed to clarify the blueschist- to greenschist-facies transition on Sifnos.

7.3. Nature of the contact between Cheronissos and Faros units

In this study, we interpret the COF contact as a top-to-the-northeast ductile shear zone as proposed by Trotet et al. (2001a) (Figs. 4 and 14). At small-scale, local brittle deformation may be observed, but not to the point of suggesting a large-scale brittle detachment. Locally, brittle or brittle-ductile kinematic indicators with a top-to-the-SW sense of shear are observed, which led Ring et al. (2011) to suggest that this contact belongs to a top-to-the-south detachment system. Our observations indicate instead that these kinematic indicators are related to the south-dipping late-stage normal faults that cut through the regional foliation.

This shear zone along the COF contact is coeval with the greenschist-facies deformation observed in the whole Faros Unit, and more locally in Cheronissos Unit, as well as along a few localized shear zones such as the Chryssopigi Shear Zone. The COF Shear Zone thus belongs to a thick strain localization zone that encompasses the whole Faros Unit with a downward gradient of strain and progressive downward localization through time, with local smaller scale shear zones where shearing has been preferentially partitioned. We then refer to this thick shear zone as the Apollonia Shear Zone.

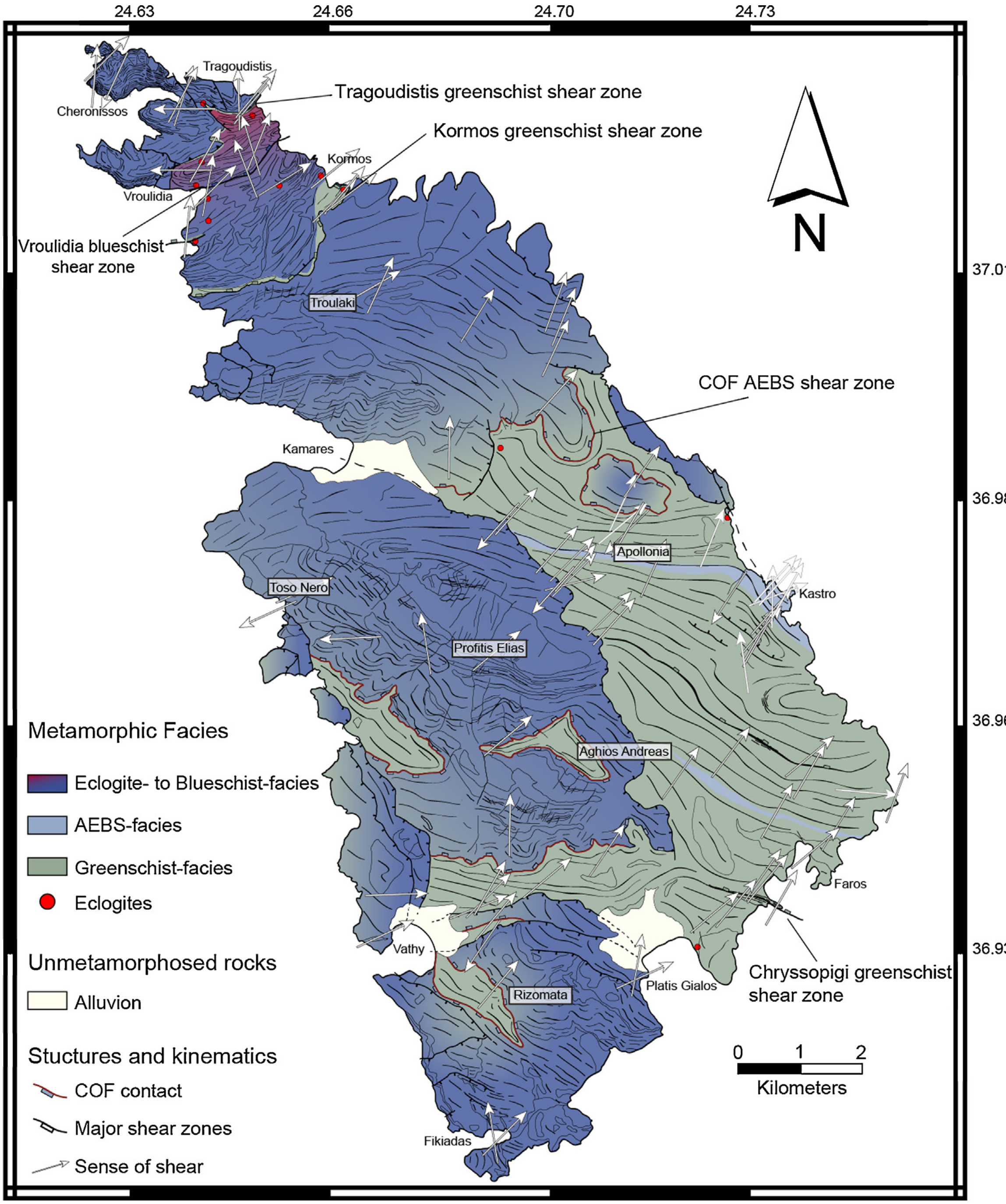

Fig. 14. A new metamorphic map of Sifnos.
Colours correspond to the dominant metamorphic facies observed in the field and colour gradients show the gradual transitions due to progressive top-to-the-NE shearing deformation and coeval retrogression (red shows dominant eclogite-facies, blue dominant blueschist-facies and green dominant greenschist-facies). The white arrows indicate the sense of shear in all units. The main shear zones are indicated in the map.(For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

7.4. Evolution of shear zones and strain localization

Although some uncertainties remain on the detailed P-T evolution, we show that, from the Eocene (45 Ma) to the Miocene (19 Ma), a continuum of syn- *syn*-blueschist to syn-greenschist top-to-the-N/NE shearing along the Apollonia Shear Zone accommodated the exhumation. In the northern part of the island, peak to retrograde HP-LT deformation is locally well preserved near Vroulidia, without significant greenschist-facies retrogression nor deformation. This part of the top-to-the-north shear zone was thus deactivated early in the exhumation process. The deformation is progressively localized within the major Apollonia Shear Zone, toward the base of the CBU of Sifnos during exhumation. This large-scale structure appears to be more retrograded (from AEBS- to greenschist-facies) toward its lower part. Moreover, progressive localization of deformation is linked with a rejuvenation of apparent ages, from northern (around 47 Ma) to southern (30–19 Ma) part of the island, especially shown by $^{40}Ar/^{39}Ar$ and Rb-Sr data on phengite (see compilation on Fig. 3a and b; Altherr et al., 1982; Wijbrans et al., 1990; Ring et al., 2011; Bröcker et al., 2013). Hence, from a geodynamic point of view, we propose that this progressive downward localization of strain first occurred at the stage of exhumation within the subduction channel (Eocene, syn-orogenic exhumation *sensu* Jolivet et al., 2003). In a later stage, strain localization occurred within the back-arc region (Oligocene to Miocene, post-orogenic exhumation). The observed shear zones, in the AEBS- or greenschist-facies, tended to localize due to rheological contrast along lithological boundaries such as the base of the Main Marble Unit. Some shear zones (e.g., Chryssopigi) are localized within a single lithological unit. Hence, the downward migration of deformation could be linked to 1) the initial lithological heterogeneity of the CBU. Shear zones were thus active during syn-orogenic and post-orogenic stages of exhumation showing that the kinematic of the Aegean extension in the Oligocene to Miocene was influenced by heterogeneities created during burial and syn-orogenic stage; 2) an intense fluid circulation which is reflected by many syn-kinematic veins; 3) increased thermal influx at the base of the metamorphic pile as suggested by various authors (Matthews and Schliestedt, 1984; Schliestedt and Matthews, 1987; Avigad, 1993; Trotet et al., 2001b). Whatever the actual cause for this downward strain localization one important consequence is that it leaves the upper part of the accretionary complex preserved from late deformation and allows it to reach the surface almost intact. This process of progressive localisation is important to explain how pristine blueschists-facies or eclogite-facies units can now be observed at the surface.

7.5. Tectono-metamorphic evolution of Sifnos

Our observations of the tectono-metamorphic evolution of the cycladic blueschists of Sifnos show that, after a phase of prograde top-to-the-SE shearing (Aravadinou et al., 2015), exhumation involved a top-to-the-NE shearing coeval with decompression and progressive localization of strain in the lower part of the tectonic pile, from the Eocene to the Early Miocene. This evolution thus encompasses both the syn-orogenic stage within the subduction zone and the post-orogenic stage in a back-arc position.

In more details the tectono-metamorphic evolution of Sifnos can be summarized in four stages (Fig. 15):

- Before 47 Ma, during the convergence between African and Eurasian plates and the subduction of the Pindos oceanic basin below the southern margin of Eurasia, the CBU of Sifnos recorded a first deformation phase in the subduction channel, creating an early foliation S_1, only preserved as inclusions in garnets, in particular in the northern part of Sifnos where HP-LT parageneses are well preserved. The sporadic preservation of S_1 structures does not allow constraining the kinematics associated with this first deformation stage. However, we interpret the large-scale folds observed in the northern part of the island as the consequence of this first ductile deformation event (Figs. 4, 7 b and c). This top-to-the-SSW kinematics may be related to the top-to-the-SE shearing described on Sifnos by Aravadinou et al. (2015) or the top-to-the-SW sense of shear described in the CBU on Syros Island by Philippon et al. (2011) and interpreted by these authors as synchronous with the prograde high-pressure deformation phase. On Sifnos, during this first stage of deformation in the mid-Eocene, the Marble Complex, Eclogite-Blueschist Unit and Main Marble Unit were respectively thrust southward on the top of Faros Unit, but the amount of displacement cannot be further constrained. All rocks of Sifnos have probably recorded this prograde top-to-the-SW kinematics that was almost completely overprinted by the later deformation phases.
- Between 47 and 30 Ma, the metamorphic rocks of Sifnos reached peak P-T conditions and started their exhumation. During this syn-orogenic exhumation period, a syn-blueschist deformation phase has resulted in the formation of the foliation in Eclogite-Blueschist Unit with top-to-the-N to −NE sense of shear (Fig. 14). Many folds have developed during this phase, some with their axes perpendicular to the transport direction; locally, a-type folds were formed indicating a strong non-coaxial shearing component.
- From 30 Ma, which corresponds to the beginning of post-orogenic extension and formation of the Aegean Sea, P-T conditions evolved from AEBS- to greenschist-facies conditions. During this phase, the deformation was mainly distributed in the whole Faros Unit, and more locally in Cheronissos Unit. Kinematic criteria indicate a top-to-the-NE sense of shear. The entire Faros Unit can be interpreted as a thick shear zone (Apollonia Shear Zone) with strain localization along the COF contact and, later, near the base of Faros Unit along discrete shear zones such as the Chryssopigi Shear Zone (Fig. 14). Extensive downward greenschist-facies overprint during this event may be related to enhance fluid circulation and increased thermal influx at the base of the metamorphic pile (Matthews and Schiestedt, 1984; Schiestedt and Matthews, 1987; Avigad, 1990; Trotet et al., 2001b).
- Between 19 Ma and Present, the timing of CBU exhumation is constrained by zircon fission track data (Ring et al., 2011). ZFT ages of 13–10 Ma suggest that Faros Unit was exhumed across the 250–300 °C isotherm during this period. The youngest ages associated with ductile deformation are those obtained on micas with the $^{40}Ar/^{39}Ar$ method (Wijbrans et al., 1990) around 19 Ma. The late folds F_3 developed during the beginning of this period and they refold both Faros and Cheronissos Unit. The southwest-dipping normal faults that offset the main COF contact are locally low-angle structures displaying brittle-ductile microstructures Fig. 5c and g). However, their throw is not large and it is difficult to say whether these structures had a significant effect on the final exhumation of Faros Unit. Therefore, the timing of the transition from top-to-the-NE ductile shearing to late brittle top-to-the-SW normal faults observed on Sifnos is not well constrained. Similar SW-dipping listric normal faults and flat-ramp system have been described respectively on Folegandros Island (Augier et al., 2015) and on Syros Island (Philippon et al., 2011). Like on Sifnos, faults crosscut there the metamorphic pile of the CBU and the greenschist-facies foliation, which are both associated with ductile top-to-the-north shear sense. The significance of these SW-dipping faults is debated. Ring et al. (2011) interpreted the contact between Cheronissos and Faros Unit as a top-to-the-SW brittle detachment, which they coined as the "Sifnos detachment" belonging to the "South Cycladic Detachment System" outcropping on the islands of Serifos, Ios and Sifnos. The top-to-the-south sense of shear previously described on Ios (Lister et al., 1984) has been reinterpreted by Huet et al. (2009) as a thrust-related shearing event, thus predating the top-to-the-north Aegean extension. In a more recent paper, Mizera and Behrmann (2015) have addressed this debate again and argued in favour of the extensional model for the Cycladic Blueschist/Basement Unit contact on Ios. They have studied the distribution of kinematic indicators and quantified the amount of stretching in the basement orthogneiss and concluded that the basement has been stretched and flattened by respectively 70% and 40%. They use the upward strain gradient in the basement to conclude that the contact was mainly extensional and they estimate the total displacement during extension to some 13 km. They also recognized that, before extension, the main contact had to be a thrust as shown by Huet et al. (2009). The main point of disagreement stems from different interpretations of the deformation in the basement. Huet et al. (2009) did not consider that the upward strain gradient in the basement was indicative of extension and we stick to their interpretation. It shows the existence of a major shear zone there, but it does not say whether it was extension or compressional. Besides, the late extension is clearly shown in the overlying cycladic

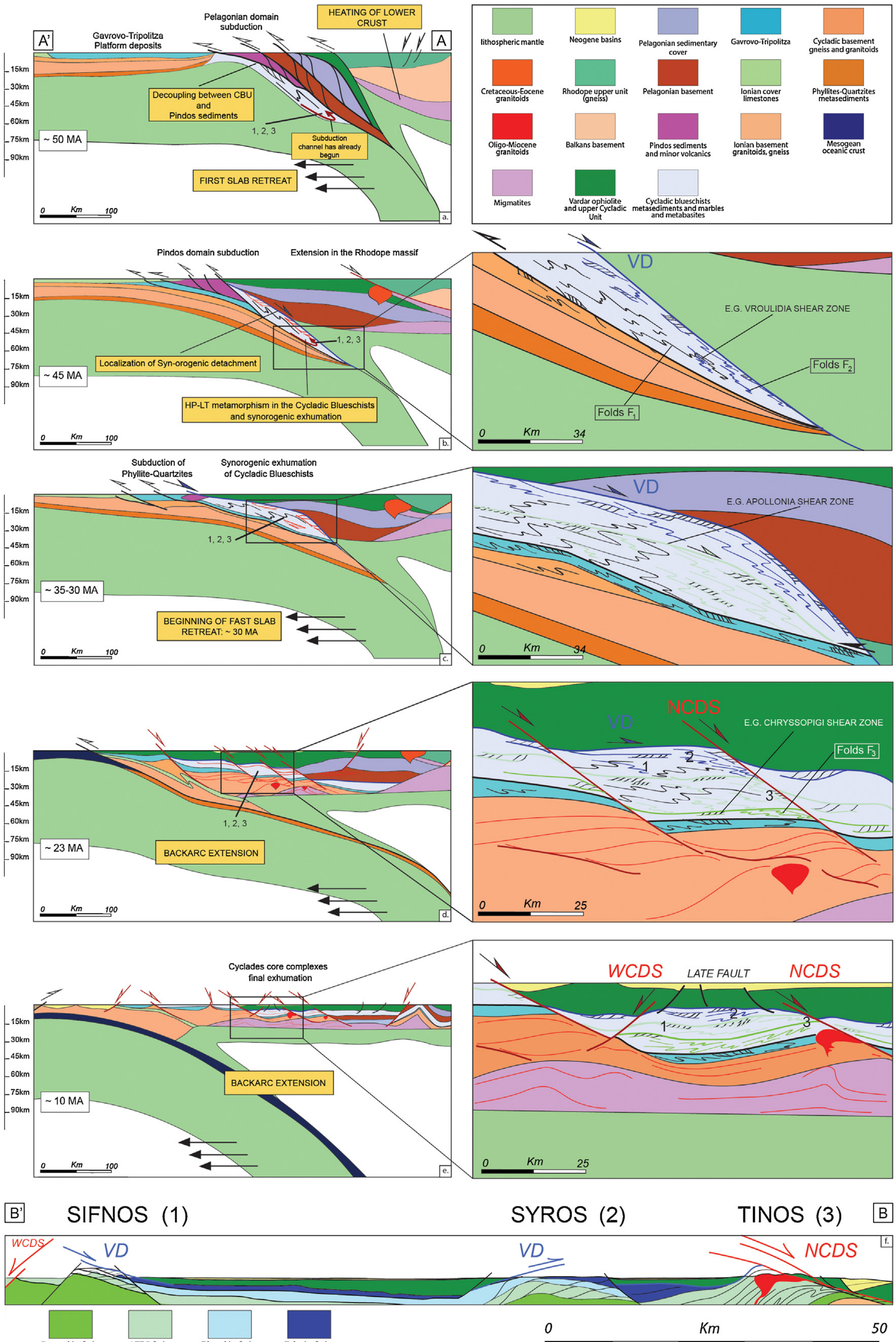

Fig. 15. Series of step-by-step north-south cross-sections of the Aegean domain from 65 Ma to 10 Ma modified after Jolivet and Brun (2010). See location in Fig. 1a. Reconstructions indicate the tectono-metamorphic evolution of Sifnos, Syros and Tinos, respectively shown by numbers 1, 2 and 3. The last cross-section, see location in Fig. 1b, showing the Present geometry of these islands. Abbreviations WCDS, VD, NCDS indicate respectively the West Cycladic Detachment System, the Vari Detachment and the North Cycladic Detachment System.(For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

blueschists by retrograde top-to-the-N shear bands at all scales, while top-to-the-S syn-blueschists shearing has been preserved only in the vicinity of the main contact. Such intense top-to-the-N shearing, that Huet et al. (2009) attribute to extension is observed all over the island, also in the main contact and it is difficult to confidently say whether the top-to-the-N and top-to-the-S shear zones in the basement were coeval or not.

Grasemann et al. (2012) have described the West Cycladic Detachment System (WCDS) exposed on Kea, Kythnos and Serifos Islands. The WCDS consists in two main detachments, a ductile one intruded by a granodiorite pluton and a brittle one cutting the roof of the same pluton (see also Rabillard et al., 2015). The sense of shear on the WCDS is everywhere top-to-the-south, from Serifos all the way to Lavrion (Fig. 1b). Based on our new field observations of the deformation recorded on Sifnos and especially along the contact between Cheronissos and Faros units, we propose an interpretation significantly different from that of Ring et al. (2011) who associated Ios and Sifnos within the South Cycladic Detachment. As Augier et al. (2015) on Folegandros Island and Jolivet et al. (2015), we suggest to associate the top-to-the-SW faults that offset the COF Shear Zone to a brittle expression of the WCDS that may be extended from Serifos to offshore Sifnos. In this scenario, the N-S-trending normal faults dipping either west or east on either sides of the island are taken to reflect the latest brittle stages accommodating the end of exhumation on Sifnos.

7.6. *Implications for the exhumation of the Cycladic Blueschist Unit (CBU)*

Current assumptions on the tectonic and metamorphic history of the CBU need to be revised in the light of our new observations. Forster and Lister (2005) proposed a reconstruction involving the succession of several subduction/exhumation episodes with repeated inversion of the sense of motion along the main contacts. However, the exhumation of the CBU is mainly characterized by a top-to-the-N to −E ductile deformation since the Eocene with, most notably, the same metamorphic peak conditions across the whole pile. These can hardly be reconciled with the inversions hypothesized for the evolution of the CBU on Sifnos. Based on the extrusion wedge model of Chemenda et al. (1995), Ring and Reischmann (2002) suggested a decoupling of crustal units accommodated by a detachment at the top and a thrust at the base to explain a part of CBU exhumation. Brun and Faccenna (2008) proposed a similar model with an extreme localization of strain at the top and base of the CBU, their model also emphasizing the importance of slab retreat to favour exhumation. However, our field observations show the existence of several shear zones active since the Eocene during exhumation, showing that the CBU did not behave as a single coherent unit.

This study has clarified some of the uncertainties about the general structure of the CBU of Sifnos, which shows some similarities with Syros Island. Indeed, on Syros the metamorphic peak is estimated around 20kbar and 500–550 °C (Trotet et al., 2001b) and dated around 52 Ma (Lagos et al., 2007). The HP-LT parageneses are also well preserved and the syn-exhumation kinematics are characterized by top-to-the-E sense of shear active in blueschist-facies and greenschist-facies conditions (Trotet et al., 2001a,b; Laurent et al., 2016). Hence, the overall structure of Syros is very similar to that of Sifnos with the notable addition of the Vari Detachment cropping out on Syros. Both islands show the same architecture with the uppermost units below the main detachment displaying the best-preserved HP-LT parageneses with a progressive localization of deformation toward the base of the tectonic stack during exhumation (see Trotet et al., 2001a and Laurent et al., 2016 for Syros Island). However, this Eocene syn-orogenic exhumation gradient is associated with different shearing directions (E-verging on Syros, N-NE-verging on Sifnos; Trotet et al., 2001a,b). Everywhere else, the CBU shows mostly top-to-the-N or NE kinematic indicators related to syn-blueschist exhumation. These are found to vary according to their position within the arc subduction, north-directed in the front, (e.g., Ios), more east-directed on the northern side of the arc (e.g., Andros, Tinos, Fig. 1b).

The history of exhumation of the CBU thus involved a thrust at the base (seen on Ios or Sikinos), a main detachment at the top (the Vari Detachment seen on Syros; Trotet et al., 2001a; Soukis and Stöckli, 2013; Laurent et al., 2016) and a distribution of strain within the exhumed unit along a series of shear zones synthetic of the main upper detachment (top-to-the-N or −E). So the exhumation scenario should be intermediate between the extrusion mode where all the deformation is concentrated at the top and base and a subduction channel in the sense of England and Holland (1979) or Shreve and Cloos (1986) where the deformation is fully distributed. We suggest that HP units are progressively detached from the subducting lithosphere when they reach the peak of pressure by top-to-the-S syn-HP thrusts and are then exhumed within the channel, progressively sheared top-to-the-N or −NE when the approach the roof of the channel, like in Jolivet et al. (2005). Precisely dating the peak of metamorphism in the different units as well as strain localization along the main shear zone would help reaching a consensus on this question.

After the Eocene syn-orogenic episode, exhumation was completed from 35 to 30 Ma during the formation of the Aegean Sea by crustal thinning and accommodated by the NCDS (Jolivet et al., 2010), the Naxos-Paros detachment (Gautier et al., 1993) or the WCDS (Grasemann et al. (2012). This post-orogenic exhumation is characterized by a progressive localization of deformation along extensional shear zones and a consistent sense of shear during the Oligo-Miocene. It is well expressed on Tinos, marked by a NE-SW gradient of non-coaxial strain across a major extensional shear zone (Parra et al., 2002). A greenschist-facies deformation gradient, associated to the NCDS, separates the CBU from the Upper Unit. The top-to-the-north retrograde shearing deformation observed on Ios is probably related to this episode (Huet et al., 2009). Radiometric ages show that this episode is also recorded on Sifnos during the late localization of shearing toward the deep parts of the edifice.

We then suggest that south-dipping brittle normal faults are the brittle expression of the WCDS. The CBU of Sifnos are localized within the footwall of the WCDS, just as Kea, Kythnos and Serifos, but probably deeper and they did not see the intense ductile shearing associated with the WCDS, they only recorded this extension as some late brittle normal faults. Similar south-dipping normal faults are observed on Folegandros Island, further to the southeast and these are the only expression of the WCDS there. At this period, the CBU of Sifnos has undergone penetrative top-to-the-NE deformation whereas the CBU of Serifos has recorded post-orogenic deformation with top-to-the-W sense of shear. A possibility is that the main detachment (WCDS) associated with ductile deformation dies out toward the southeast or reaches the surface off the west coast of Sifnos and Folegandros Islands.

Combining our new structural observations with published petrological and geochronological data, we propose a tectonic model for the exhumation of the CBU in the Aegean domain with particular emphasis placed on evolution of the Cycladic islands of Sifnos, Syros and Tinos. The initial lithospheric scale geometry of the subduction and the disposition of the different units are taken from Jolivet and Brun (2010). Our model is presented as a series of step-by-step north-south cross-sections of the Aegean domain from 50 Ma to the present day with different numbers tracking the evolution of Sifnos (1), Syros (2) and Tinos (3) (see Fig. 15).

Early Eocene (50Ma) to Late Eocene-Early Oligocene (30–35 Ma):

Convergence between the African and Eurasian plates leads the Pindos oceanic crust and margin to reach peak pressure at 20 kbar around 52 Ma and form the CBU at depth (Fig. 15a). Relics of top-to-the-south shearing related to this episode are only locally preserved on Sifnos in the form of few kinematic indicators (Aravadinou et al., 2015) or the large F_1 folds. Top-to-the-south shearing deformation is better preserved on Ios (Huet et al., 2009) and also locally on Syros (Philippon et al., 2011). During this episode, thrusting propagates southward and leads to crustal thickening with nappe stack forming at the expense of the Pindos Ocean and Pelagonian Domain (Fig. 15a). In the early-middle Eocene, around 45 Ma, the CBU started to exhume with a cold retrograde P-T path (Trotet et al., 2001a) while the thrust at its base was still active (Huet et al., 2009). This fast exhumation is accommodated by the Vari Detachment that crops out on Syros Island, representing at this period the roof of the subduction channel (Huet et al., 2009; Jolivet and Brun, 2010; Augier et al., 2015; Laurent et al., 2016) as well as several smaller-scale coeval shear zones with the same kinematics. Just below the Vari Detachment, HP-LT parageneses are well preserved and increasingly retrograded downward with a progressive localization of deformation toward the base of the tectonic stack during exhumation (Fig. 15b). During this period, deformation proceeds mostly in the blueschist-facies with evidence of top-to-the-N to −NE sense of shear and some strain localization, in the subduction channel, as in Vroulidia (Fig. 15b) (Eocene, syn-orogenic exhumation).

Late Eocene to Late Miocene (35–10 Ma):

After a drastic change in the boundary conditions due to a second-stage of slab roll-back at 30–35 Ma (Fig. 15c; Jolivet and Faccenna, 2000; Jolivet and Brun, 2010), thrusting continues to propagate southward in the Apulian platform, whereas in the back-arc region the detachment activity increases because of enhanced rollback. At the scale of the CBU, the deformation is still mainly localized below the Vari Detachment but progressively propagates within the lower parts of the CBU. Syn-AEBS-facies shear zones associated with a top-to-the-NE asymmetric kinematic develop along lithological boundaries such as the base of the Main Marble Unit in Sifnos (COF Shear Zone) and later evolve toward greenschist-facies shear zones during exhumation (Fig. 15c). Altogether these shear zones make the Apollonia Shear Zone. During this period, slab retreat accelerates and back-arc extension is accommodated by a system of post-orogenic detachments, the NCDS and the WCDS, exhuming metamorphic core complexes of the northern and western Cyclades. Slab retreat leads to the replacement of the lithospheric root by the hot asthenosphere in this area, leading to partial melting and the progressive formation of HT core complexes as in Mykonos, Naxos (Fig. 15d; Jolivet and Brun, 2010) or Ikaria (Laurent et al., 2015; Beaudoin et al., 2015; Jolivet et al., 2015) in the Middle Miocene. In the latest stages, granodioritic plutons intrude these core complexes and detachments migrate upward in the crust.

The respective contributions of the Vari Detachment and the NCDS and WCDS in the exhumation of the CBU are not well constrained. The syn-orogenic Vari Detachment has accommodated only a part of the HP-LT rocks exhumation while post-orogenic detachments such as the NCDS crosscut or rework the Vari Detachment and accommodated the last part of rocks exhumation (Fig. 15d). Very little retrogression in greenschist-facies conditions below the Vari Detachment is observed on Syros and Tinos because most of the post-orogenic extension was accommodated on other detachments, such as the NCDS as well as on deeper shear zones such as the Apollonia Shear Zone. When the exhumed material enters the brittle-ductile transition zone, it is exhumed beneath the NCDS or WCDS and is deformed by such shear zones in the greenschist-facies and later in brittle conditions (Fig. 15d). This continuum of extensional strain from ductile-to brittle regime is also particularly well shown in the footwall of the NCDS on Tinos or Andros islands (Jolivet et al., 2004; Mehl et al., 2005, 2007).

During the post-orogenic period, the CBU followed different exhumation paths as recorded on Tinos, Syros and Sifnos. In Fig. 15e, Tinos Island (3) is localized close to the NCDS deeper in the crust whereas Syros (2) and Sifnos (1) have already been largely exhumed just below the Vari Detachment. The whole CBU on Tinos shows a much more intense retrogression in the greenschist-facies than Syros and Sifnos islands, except for those outcrops located on the south-western flank of the foliation dome (Gautier and Brun, 1994; Jolivet et al., 2004; 2010). On Sifnos and Syros, the best-preserved part of the CBU is much thicker and only the lower part is strongly retrograded. This suggests that on Tinos, closer to the NCDS, finite exhumation during the post-orogenic stage has been more important. This late exhumation shows mostly the deepest part of the CBU, strongly retrograded, with the syn-greenschist retrogression along the NCDS itself.

Early Late Miocene (10 Ma) to the present

Around 10 Ma, back-arc extension localized in the Cretan Sea giving rise to local crustal necking, whereas a constant thickness of ~26 km persisted below the hottest part of the Cyclades (Jolivet and Brun, 2010). At around 5 Ma, extension migrated in the northern part of the Aegean domain along the North Anatolian Fault and along the Corinth Rift and the Menderes grabens in western Turkey. As shown by Sanchez-Gomez et al. (2002) and Kuhlemann et al. (2004), the absence of the CBU clasts in continental Miocene basins (8–10 Ma) implies that CBU did not outcrop at this time. The end of the exhumation was accommodated by the brittle deformation that controlled the current geometry of Cycladic islands (Fig. 15f and see location of cross-section Fig. 1b). Around 10 Ma, the metamorphic domes were already formed and close to the surface.

8. Conclusion

In this study, new geological and metamorphic maps at the scale 1:20,000 have been redrawn leading us to reconsider the history of exhumation of the Cycladic Blueschist and discuss published models. The CBU of Sifnos shows several units with different degree of retrogression of HP-LT parageneses. The Cheronissos Unit, which contains well preserved eclogite and blueschist parageneses overlies the Faros Unit where retrogression in the greenschist-facies is intense and HP-LT parageneses are preserved only locally. The main retrograde deformation is associated with a top-to-the-NE sense of shear that is more intense within the Faros Unit. In particular, this unit behaved as a major top-to-the-NE large-scale shear zone (the Apollonia Shear Zone), active throughout the retrograde P-T path from AEBS- to greenschist-facies conditions. Toward the base of the tectonic pile, shearing was characterized by localization of strain along progressively more restrained volumes and therefore thinner shear zones. An earlier deformation is associated with retrograde blueschist-facies parageneses after the peak metamorphic conditions in the eclogite-facies, with a top-to-the-N to −NE sense of shear. Continuous deformation lasted with the same top-to-the-NE sense of shear from the Eocene syn-orogenic blueschist-facies to the Oligocene-Miocene post-orogenic greenschist-facies, showing that the shear zones formed during syn-orogenic exhumation were continuously deformed and/or reactivated during the formation of the Aegean back-arc (see also Gautier and Brun, 1994). Late low-angle and steeper normal faults with top-to-the-SW to −S kinematic indicators crosscut the ductile structures. In our interpretation, they may be the brittle expression of the West Cycladic Detachment System. We propose a model of progressive exhumation, first in the subduction channel of the Hellenic subduction and then in the back-arc region with the same top-to-the-NE non-coaxial component of shearing. Deformation tends to localize downward through time during exhumation leaving the upper parts of the subduction complex preserved from late deformation, thus reaching the surface almost intact. The main discontinuities allowing this exhumation are the Vari Detachment cropping out on Tinos and Syros islands during the syn-orogenic period (Eocene) and then the NCDS and WCDS afterward.

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